PROJECT PATHFINDER

PLANETARY ROVER PROJECT PLAN

Fall 1988

PATHFINDER

Office of Aeronautics and
Space Technology

National Aeronautics and
Space Administration
Washington, D.C. 20546

PATHFINDER PLANETARY ROVER PROJECT PLAN

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SEPTEMBER 1, 1988

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PATHFINDER PLANETARY ROVER
PROJECT PLAN
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FORWARD

Project Pathfinder is an important technology initiative which will allow the National Aeronautics and Space Administration (NASA) to develop critical capabilities to enable future space missions. Pathfinder does not, in itself, represent a commitment to any particular mission. Nevertheless, Project Pathfinder will make future national decisions regarding human exploration of the Solar System possible. Through Pathfinder, the NASA Office of Aeronautics and Space Technology (OAST) will develop a variety of high-leverage technologies that will support a wide range of potential future NASA missions.

The Pathfinder Planetary Rover Program will develop and validate the technologies needed to enable both robotic and piloted exploration of various planetary surfaces. In its first phase, the program will be focused on robotic rover technologies needed for a Mars Rover Sample Return (MRSR) mission such as navigation, mobility, power, autonomy and computation.

For additional information on the Planetary Rover Program, or this document, please call the OAST Information Sciences and Human Factors Division, at (202) 453-2747.

TABLE OF CONTENTS

FOREWARD

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

GLOSSARY

1. INTRODUCTION

1.1. Document Purpose and Scope
1.2. Program Goal and Objectives
1.3. Program Approach and Elements
1.4. Program Background and Need

2. PLANETARY ROVER CHARACTERISTICS

2.1. Operational Characteristics
2.2. System Functional Architecture

3. APPLICATIONS

4. TECHNOLOGY AREAS

5. TECHNOLOGY DEVELOPMENT PLAN

5.1. Navigation
5.2. Mobility
5.3. Power
5.4. Operations/Autonomy
5.5. Computation
5.6. Architecture
5.7. Systems Integration
5.8. Thermal Control
5.9. Communications
5.10. Piloted Rover Technology
5.11. Autonomous Mining/Construction Rover Technology

6. PROGRAM MANAGEMENT

6.1. Organization
6.2. Reviews
6.3. Reporting
6.4. Facilities

7. RELATED NASA AND DOD PROGRAMS

7.1. NASA Pathfinder Sample Acquisition, Analysis and Preservation
7.2. DARPA Autonomous Land Vehicle Program
7.3. U.S. Army Robotic Vehicle Technology Program

8. COLLABORATION WITH OTHER AGENCIES/INDUSTRY/UNIVERSITIES

9. SCHEDULE

10. FUNDING

11. MANPOWER

APPENDIX A. TECHNICAL WORK PACKAGES FOR NASA CENTERS

A.1. AMES RESEARCH CENTER
A.1.1. Navigation
A.1.2. Operations/Autonomy

A.2. JET PROPULSION LABORATORY
A.2.1. Navigation
A.2.2. Mobility
A.2.3. Power
A.2.4. Operations/Autonomy
A.2.5. Computation
A.2.6. Systems Integration

A.3. LEWIS RESEARCH CENTER
A.3.1. Power - Sodium Sulphur Battery

LIST OF TABLES

TABLE 1	TECHNOLOGY SUMMARY MATRIX
TABLE 2	MILESTONES
TABLE 3	FUNDING SUMMARY
TABLE 4	FUNDING SUMMARY (ELEMENT FUNDING BY CENTER)
TABLE 5	MANPOWER SUMMARY

LIST OF FIGURES

FIGURE 1	MARS ROVER SAMPLE RETURN MISSION
FIGURE 2	PLANETARY ROVER FUNCTIONAL ARCHITECTURE
FIGURE 3	COMPUTER AIDED REMOTE DRIVING
FIGURE 4	SEMIAUTONOMOUS NAVIGATION
FIGURE 5	CMU LEGGED LOCOMOTION CONCEPT
FIGURE 6	PATHFINDER PLANETARY ROVER SCHEDULE MILESTONE

GLOSSARY

A&R	Automation and Robotics
AI	Artificial Intelligence
ARC	Ames Research Center
CARD	Computer Aided Remote Driving
CMU	Carnegie Mellon University
CRAF	Comet Rendezvous and Asteroid Flyby
CSTI	Civil Space Technology Initiative
DSN	Deep Space Network
DOD	Department of Defense
DOE	Department of Energy
EVA	Extra Vehicular Activity
FY	Fiscal Year
GHZ	Gigahertz
JPL	Jet Propulsion Laboratory
KG	Kilogram
KW	Kilowatt
LaRC	Langley Research Center
LeRC	Lewis Research Center
M	Meter
MMIC	Millimeter Wave Integrated Circuit
MRSR	Mars Rover Sample Return Mission
NASA	National Aeronautics and Space Administration
OAST	Office of Aeronautics and Space Technology
OEXP	Office of Exploration
OSSA	Office of Space Science and Applications
PIC	Power Integrated Circuits
PMAD	Power Management and Distribution
RTG	Radioisotope Thermoelectric Generator
SAAP	Sample Acquisition, Analysis and Preservation
SAN	Semiautonomous Navigation
SBIR	Small Business Innovative Research
SEC	Second
S/W	Software
TWT	Traveling Wave Tube

1. INTRODUCTION

1.1. Document Purpose and Scope

The purpose of this document is to provide guidance and information on the scope, content and long-range plans of the Pathfinder Planetary Rover (PPR) program. The objectives of this document vis-a-vis the program are to:

- o Provide traceability to mission-derived technology requirements
- o Specify the top-level work breakdown structure
- o Define technical goals and objectives for the program and for the major work packages
- o Define the management approach (including structure, participating centers and individual roles, responsibility and accountability)
- o Establish resource allocations and associated schedules and milestones
- o Document long-range (ie, 5 year) PPR program planning

1.2. Program Goal and Objectives

The overall goal of the PPR Program is to develop and validate technology to enable the automated and piloted exploration of extensive areas of lunar and planetary surfaces. The initial focus is on automated Martian Rover technology for exploration and science. The key technologies for automated Martian Rovers are navigation, mobility, power, operations/autonomy, computation, architecture , thermal control and communications. Development and integration of these technologies will allow orders of magnitude increase in the effectiveness of remote surface operations. Later technology needs are for rover systems for automated construction and mining, and for exploration with human-driven rovers. The generic technology requirements for manned and unmanned rovers are strongly related; the manned rover program element will be built upon the technology base developed in the earlier unmanned rover program elements.

1.3. Program Approach and Elements

The PPR program includes three major program element types; namely:

- o Advanced development of unmanned Mars Rover technology

- o An integrated Mars Rover testbed for technology validation
- o Advanced development of piloted and autonomous mining/construction rover technology

Advanced unmanned Mars Rover technology development encompasses eight program elements; namely:

- o Navigation
- o Mobility
- o Power
- o Operations/Autonomy
- o Computation
- o Architecture
- o Thermal Control
- o Communications

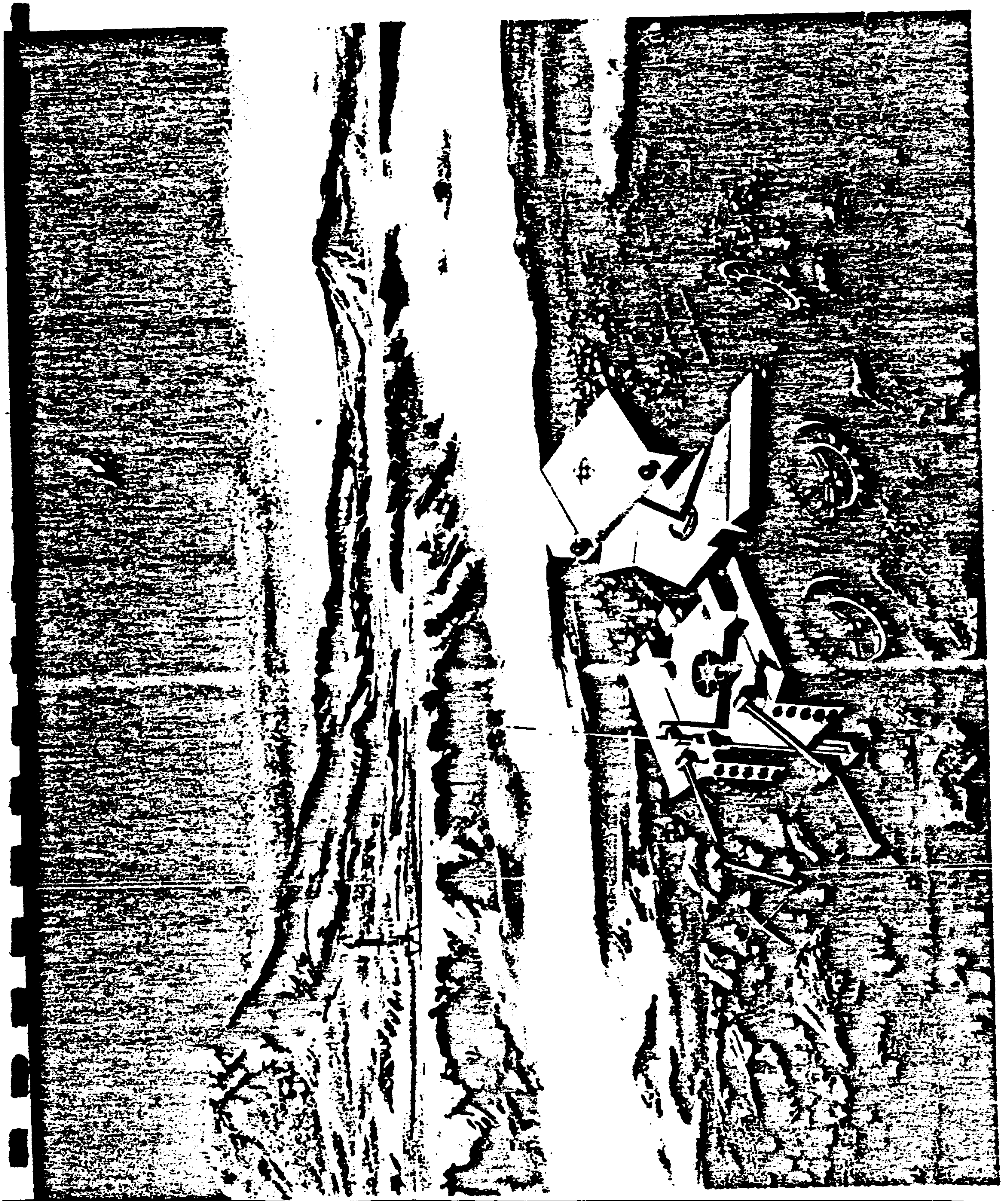
An integrated testbed will be defined and implemented under the PPR program element titled Systems Integration. This testbed will provide a focus for and a means of validating the advanced technology development elements and will serve as a mechanism for the technology transfer process.

Piloted Rover and Autonomous Mining/Construction Rover technology program elements are planned for initiation in the FY-91 time period. Detailed planning of these program elements has not yet been performed.

1.4. Program Background and Needs

A planetary (including lunar) surface mobility capability is required to support planned future National Aeronautics and Space Administration (NASA) missions identified in the 1987 NASA Space Goals Study. The Mars Rover Sample Return (MRSR) project is the initial step in the crewed Mars exploration program, and is the earliest NASA project identified as needing planetary sample return rover technology. MRSR is currently targeted for a 1998 launch, which requires technology readiness by 1992. An artist depiction of a Mars Rover is illustrated in Figure 1. Manned and unmanned rover technology to support exploration, mining and construction functions are required for the crewed Lunar and Mars missions.

The NASA Office of Aeronautics and Space Technology (OAST) has initiated the Pathfinder Planetary Rover (PPR) Program to provide the required rover technology for enabling the manned and unmanned Lunar and Mars Programs identified in the 1987 Space Goals Study.



For NASA to be successful in these future space programs, it is necessary that automated surface rover technology be developed. The key technologies for automated Martian Rovers are navigation, mobility, power, operations/autonomy, computation, architecture, thermal control and communications. Development and integration of these technologies will allow orders of magnitude increase in the effectiveness of remote surface operations. For example, it is impractical to have a Martian Rover that is teleoperated from Earth (ie, one in which individual movements are controlled from earth) because of the long signal time (average 30 minutes round trip).

2. PLANETARY ROVER CHARACTERISTICS

2.1. Mission Derived Technology Requirements

The MRSR Preproject and Mars Rover Design Team sponsored by the NASA Office of Space Science and Applications (OSSA) has established Mars Rover design reference points for future studies. Two baseline designs have been established; namely, a Phase 0 and a Phase 1 design. The Phase 0 baseline design is one which, with the exception of robust Computer Aided Remote Driving navigation, a Modular RTG power source and an advanced ground operations capability, uses state-of-the-art technology. the Phase 1 baseline design represents a much more capable rover and is based on the premise of advanced technology funding provided by the PPR program. Table 1 summarizes the baseline designs and shows the areas of enabling technology development required.

The MRSR Preproject will provide the PPR program, on a yearly basis, a statement that identifies and prioritizes the technology needs for MRSR. That statement is expected around the beginning of each new fiscal year in time to affect the preparation of the detailed task implementation planning for that fiscal year.

Other inputs, in addition to those of MRSR, which will affect the PPR program include results from Johnson Spaceflight Center (JSC) surface operation studies and from manned Lunar and Mars studies.

2.2. System Functional Architecture

In order to establish a coherent framework that aids in the identification and definition of the technology needs, it is convenient to use a system architecture which displays the major subsystem functional blocks. A strawman functional architecture is

TABLE 1
TECHNOLOGY SUMMARY MATRIX
NEW ENABLING TECHNOLOGIES ARE IN UNDERLINED BOLD PRINT

FUNCTION	PHASE 0	PHASE 1
Mode of Operation	CARD	SAN **<u>Algorithm Dev</u>** Computer on Rover
Expectation planning	Current On earth	**<u>3-D Model</u>** On Rover
Execution Monitoring	Current	**<u>Algorithm Dev</u>**
Terrain Sensing	Cameras	Cameras + Rangefinder + Mechanical Feeler
Mobility	None -	**<u>3-D Model</u>** for sim + expectation planning
Attitude sensing	CRAF	CRAF
General Purpose Processors	1 MIP Single Proc'	**<u>5 MIPS, Multiple Proc' Architecture</u>**
Special Purpose Proc'	None	**<u>Image Processor</u>**
Data storage	Magellan	**<u>High Vol & Speed</u>**
Power	Mod RTG SiGe Ni-Cad Discrete	Mod RTG Adv SiGe/GAP Li-TiS2 Batteries Int Circuits
Thermal Control	Two Phase Heat Transfer Loop and Thermal Energy Storage	
Communication	X-Band	**<u>Ka-Band</u>**
Ground Control Op's	**<u>Alg Dev</u>**	**<u>Algorithm Dev</u>**
Onboard System Exec	None	**<u>Sys Dev & Alg Dev</u>**
Performance		
Meters/Ground command cycle	5-30	1000's
Ground command cycles/sol	2-7	1 or so
Effective Range(kms traveled in a 100 day mission)	1-20	>70

shown in Figure 2. Note that although physical devices are assigned to particular functional subsystem, they are shared by other subsystems (for example, the cameras and computers might support both traverse and sampling). Note also that, while the system excludes the human operator and the outside world, both are of major consideration in determining technology requirements and system capabilities.

3. APPLICATIONS

NASA's planning for the future exploration of the Solar System includes both piloted and robotic missions to the Moon and Mars. Most, if not all, of the mission scenarios under consideration include the use of mobile surface vehicles to conduct exploration, gather samples, deploy scientific payloads and perform tasks such as construction, mining and equipment transport. The Mars Rover Sample Return (MRSR) mission currently under study is one such potential application of 'planetary rover' technologies. Scenarios involving the creation of human installations require 'rovers' to support both construction, surface mining and equipment transport operations; these systems may be autonomous, teleoperated, piloted, or a combination of the three.

4. TECHNOLOGY AREAS

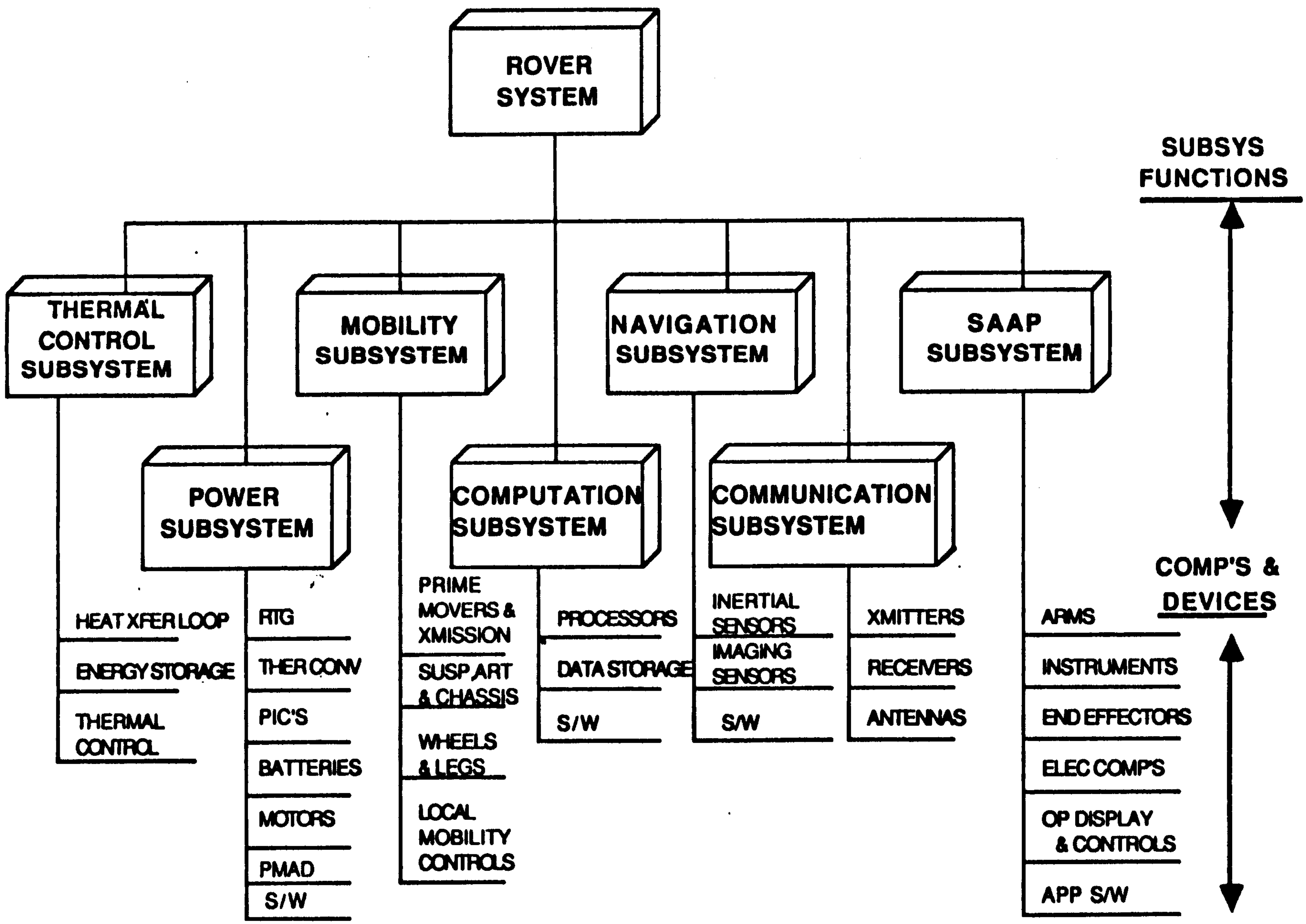
The Pathfinder Planetary Rover Program technology breakdown structure encompasses eleven program elements; namely:

- Navigation
- Mobility
- Power
- Operations/Autonomy
- Computation
- Architecture
- Systems Integration
- Thermal Control
- Communications
- Piloted Rover Technology
- Autonomous Mining/Construction Rover Technology

Each of these eleven program elements are described in the following section.

5. TECHNOLOGY DEVELOPMENT PLAN

FIGURE 2. PLANETARY ROVER FUNCTIONAL ARCHITECTURE



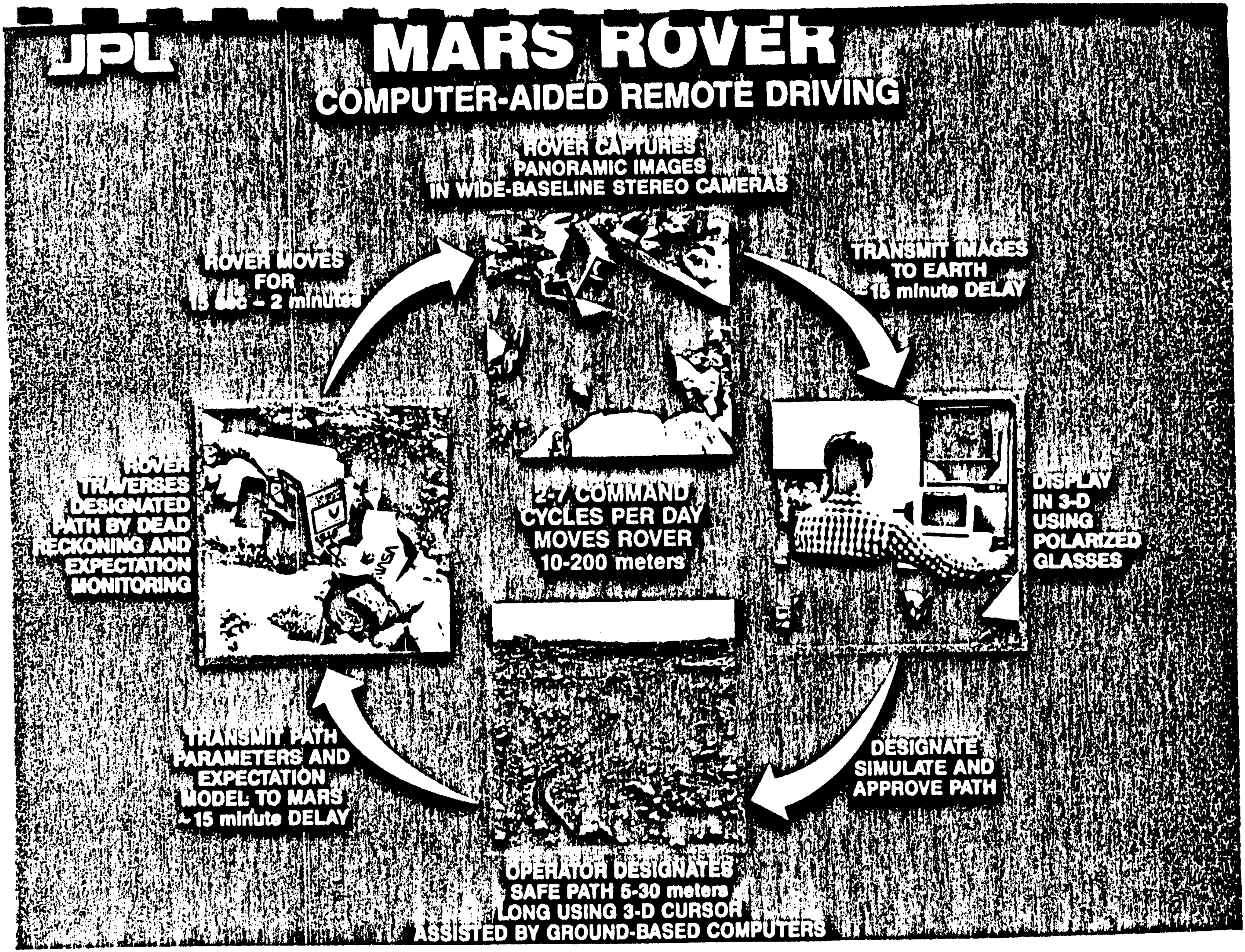
5.1. Navigation

Because of the long signal time to Mars (average 30 minutes round trip), it is impractical to teleoperate a Martian Rover from Earth (one on which individual movements are controlled from Earth). Therefore, some autonomy on the Rover is needed. A highly autonomous rover capable of traveling safely over long distances for many days in unfamiliar terrain without guidance from Earth is beyond the present state-of-the-art. In between the extremes of teleoperation and high autonomy, various degrees of autonomy are possible. Two in particular will be developed within this work element; namely, computer aided remote driving (CARD) and semiautonomus navigation (SAN). The focus of the navigation work element will be on developing the algorithms for CARD and SAN autonomous navigation and on validating those algorithms in a navigation testbed facility.

With CARD, as depicted in Figure 3, stereo pictures from the rover are sent to Earth, where they are viewed by a human operator using a stereo display. The operator designates a safe path for the vehicle to follow as far ahead as can be seen. The path is then simulated on the ground to generate rover sensor expectations (attitude, acceleration,, orientation, etc). The plan is sent to the rover which executes the path by dead reckoning navigation aided by computer vision. The expectations are also sent to the rover and are matched against the actual sensor output during path execution. Sensor readings outside of the expected ranges will cause the execution to abort. A new stereo pair of pictures is taken from the new position and the process repeats itself. Depending on the terrain, the rover might travel about 5 to 30 meters on each of these iterations. Assuming 2 to 7 command cycles per day, the daily traverse would be 10 to 200 meters.

In the SAN method, as depicted in Figure 4, local paths are planned autonomously using images obtained on the vehicle, but they are guided by global routes planned less frequently by humans on Earth. These global routes are developed from topographic map produced images obtained by an orbiting satellite.

The sequence of operations in the portion of SAN involving Earth is as follows. As commanded from Earth the orbiter takes a stereo pair of pictures (by taking the two pictures at different points in the orbit) of an area to be traversed. A spatial resolution of 1 meter is desired. The pictures are sent to Earth where they are used by a human to plan an approximate route for the vehicle to follow


JPL
MARS ROVER
COMPUTER-AIDED REMOTE DRIVING
ROVER CAPTURES PANORAMIC IMAGES IN WIDE-BASELINE STEREO CAMERAS
TRANSMIT IMAGES TO EARTH ~15 minute DELAY
DISPLAY IN 3-D USING POLARIZED GLASSES
DESIGNATE SIMULATE AND APPROVE PATH
OPERATOR DESIGNATES SAFE PATH 5-30 meters LONG USING 3-D CURSOR ASSISTED BY GROUND-BASED COMPUTERS
TRANSMIT PATH PARAMETERS AND EXPECTATION MODEL TO MARS ~15 minute DELAY
ROVER TRAVERSES DESIGNATED PATH BY DEAD RECKONING AND EXPECTATION MONITORING
ROVER MOVES FOR 15 sec - 2 minutes
2-7 COMMAND CYCLES PER DAY MOVES ROVER 10-200 meters

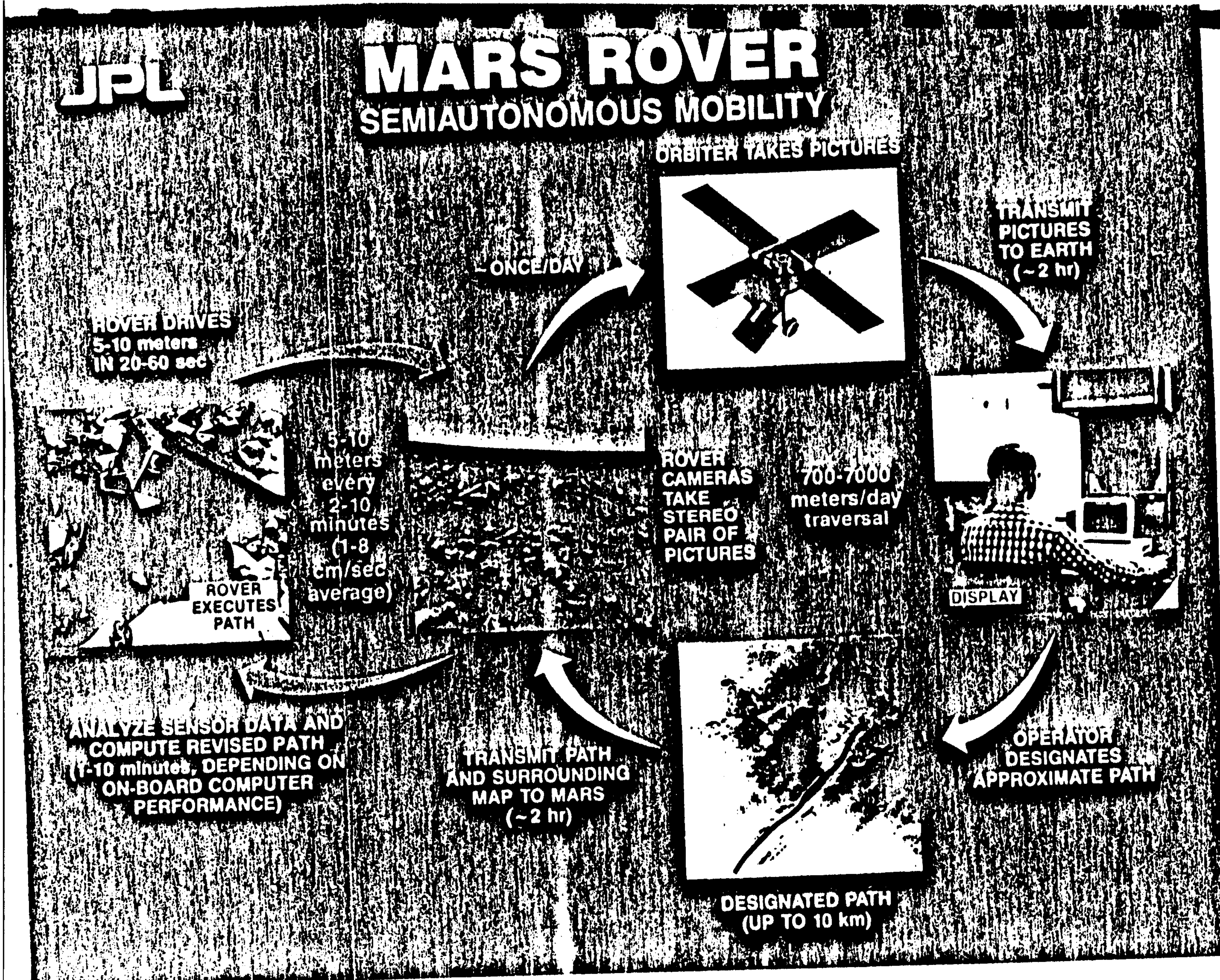
designed to avoid large obstacles, dangerous areas and dead-ends. This route and a topographic map for the surrounding area are sent from Earth to the rover. The process repeats, as needed; perhaps once for each traverse between sites where experiments are to be done, or perhaps once per day or so on long traverses.

The sequence of operations in the portion of SAN taking place on Mars is as follows. The rover views the local scene and, by using automatic stereo correlation, computes a local topographic map. This map is matched to the portion of the global map sent from earth for purposes of position determination. The high resolution local map is analyzed by computation on the rover to determine the safe areas over which to drive. A new plan is then computed, revising the approximate route from the Earth. The traverse of the revised path is simulated in order to produce sensor expectations. The expectations are used for execution monitoring and contingency planning. Using the revised path, the rover then drives ahead a short distance (perhaps 5-10 meters), and then the process repeats. Areas where it is predicted the rover may have some difficulty traversing are planned to be closely monitored and appropriate reactions pre-planned (eg, when climbing a slope of uncertain load bearing strength a tighter monitoring of wheel slippage and vehicle orientation may be maintained along with a precalculated plan for backing off the slope if the slippage exceeds some value). Assuming a daily command/execution cycle, a daily travel of 700 to 7000 meters is feasible.

The current state-of-the-art is rudimentary demonstration of CARD and SAN technology (eg. no proximity contact sensing, no surface property determination, no expectation planning, no execution monitoring, etc)

The technology needs include:

- o World sensing and perception accomplished via multiple sensor and algorithm fusion weighted by certainty, time and sensor source.
- o Surface property determination via correlation of contact and non-contact sensor data and algorithmic/heuristic driven responses to results
- o Robust path planning using multiple models and degraded terrain knowledge bases.
- o Expectation planning and execution monitoring and replanning for dynamic response to uncertainty in sensed and perceptual data.


JPL
MARS ROVER
SEMIAUTONOMOUS MOBILITY
ORBITER TAKES PICTURES
~ONCE/DAY
TRANSMIT PICTURES TO EARTH (~2 hr)
DISPLAY
OPERATOR DESIGNATES APPROXIMATE PATH
DESIGNATED PATH (UP TO 10 km)
TRANSMIT PATH AND SURROUNDING MAP TO MARS (~2 hr)
ROVER CAMERAS TAKE STEREO PAIR OF PICTURES
700-7000 meters/day traversal
5-10 meters every 2-10 minutes (1-8 cm/sec average)
ANALYZE SENSOR DATA AND COMPUTE REVISED PATH (1-10 minutes, DEPENDING ON ON-BOARD COMPUTER PERFORMANCE)
ROVER EXECUTES PATH
ROVER DRIVES 5-10 meters IN 20-60 sec

5.2. Mobility

Mobility systems for planetary rovers must combine trafficability, stability, speed and reliability over a wide variety of terrains within constraints of mass, power and volume. Foreknowledge of terrain and surface properties is very poor. A number of experimental locomotion concepts (encompassing wheeled, legged and hybrid configurations) for planetary surface operations have been built and tested (mostly for the Apollo program). New mobility designs are being studied for the MRSR mission under NASA OSSA funding. A legged locomotion concept is being investigated by Carnegie Mellon University (CMU) as part of this PPR program (see section 5.6.).

The initial focus of this work element will be to develop analytic tools to support vehicle design, control design and verification, and navigation simulation and expectation planning. Work in later years will focus on mobility component designs, emphasizing adaptability for varying terrains and rover operational modes. The analytical tools developed in the beginning of this work element will be used to identify the specific issues of the later work.

The state-of-the-art is:

- o Wheeled locomotion with moderate mobility characteristics evaluated in idealized environments (step and crevasse sizes of one and one half wheel diameters, slopes of 30 degrees in soft sand and speeds of 1 meter/second)
- o Three dimensional (3-D) vehicle/terrain modeling for higher speed vehicles (commercial and military) than those of interest
- o Lunar rover wheel packaging and deployment concepts/technologies

The technology needs include:

- o A practical, high mobility locomotion system with low mass and volume and low power consumption
- o A general 3-D model of vehicles moving over general terrain at the low speeds of interest is required for comparative assessment of locomotion options, vehicle dynamics and control verification, expectation generation for ground command verification and onboard execution monitoring.

- o Deployable locomotion concepts/technologies that offer efficient packaging of the vehicle within the volume constraints of the aeroshell
- o Adaptive mechanical system concepts/technologies that allow flexibility in response to different terrain and rover operational states (eg. high flexibility for rough terrain and high rigidity for sampling)

5.3. Power

A planetary rover requires a compact, lightweight, very high density onboard power system. In the heat source area, the requirements will be defined and a formal relationship must be established with the Department of Energy (DOE) wherein NASA can secure DOE support in Radio-isotope Thermal Generator (RTG) technology development responsive to the planetary rover requirements. In the thermal to electric energy conversion area, high efficiency conversion technology will be developed. In the energy storage area, advanced sodium sulfur and lithium titanium disulfide battery technology will be developed. In the power conditioning/control element area, advanced power integrated circuit (PIC) technology will be developed.

The state-of-the-art is represented by Galileo power technology:

- o Galileo RTGs are designed for the vacuum of space; there is no existing power source/conversion technology capable of operating a planetary rover in an atmosphere (Viking RTGs, which are not available today, provided a specific power of about 2 W/Kg)
- o Current energy storage (super nickel cadmium batteries) provide specific energy of 35 Whr/kg
- o Current power conditioning/control elements (discrete components) provide a specific power of 12 W/kg and power density of 0.06 W/cm^3

The technology needs include:

- o A planetary surface RTG energy source and thermal to electric conversion system with a specific power of 10 watts/kg
- o Increasing the specific energy of storage components (to 100 Whr/kg)
- o Increasing specific power and power density of power conditioning/control elements (to 21 W/kg and to 0.5 W/cm^3)

5.4. Operations/Autonomy

The U.S. has only operated a roving vehicle on the surface of another planetary body with the direct involvement of a human driver (Apollo Program). The remote control of the path of such a vehicle, whether the computations are performed on the vehicle or on Earth, involves an entirely unproven technology. In addition, the operations of the various rover subsystems (mobility, navigation, power, communications, etc) are highly interdependent and quire complex; thus providing a significant system operation challenge. For maximizing the mission (science) return, it is essential that Earth operations be minimized while simultaneously meeting the needs of the science community. Earth operations are minimized through the use of high level rover command sequences and rapid ground operations command cycle turnaround times. This requires a high level command language, a high level, goal directed onboard planning system and downlink data that is automatically integrated with an efficient uplink command generation process. In addition, other software tools are required for minimizing the risk of commanding unsafe behavior.

The state-of-the-art is represented by Galileo uplink command generation technology which is oriented towards repetitive tasks and one-time tasks of short duration.

The technology needs include uplink command generation of non-repetitive, long-duration tasks with an order of magnitude improvement in present command cycle turnaround time and a high level, goal directed system executive.

5.5. Computation

JPL experience in past spacecraft projects and the premise for future projects is that mission capabilities are limited by the performance of onboard computers. Thus it behooves computer developers to maximize the computer capability for future spacecraft missions.

Unmanned rover computation requirements include general purpose and special purpose, fault tolerant, fast processing speed, low power consumption, low mass, space qualified computers organized in a distributed processing architecture. High speed, high capacity mass data storage is also required. The initial focus of the work in this work element will be placed on algorithm and computational requirements leading to architecture and conceptual design.

The state-of-the-art is the Comet Rendezvous Asteroid Flyby (CRAF) flight computer (ten-32016 processors with 0.25 million instructions per second (MIPS)/processor, 20 W/MIPS and 300 components/processor) and digital tape recorder (sequential access) technology.

The technology needs include:

- o 5-10 MIPS general purpose computer with 1-4 MIPS/processor, 4-8 W/MIPS and 50-100 components/processor
- o 200 MIPS special purpose image processor
- o High performance data storage with random access capability

5.6. Architecture

Architectural issues critical to autonomous exploration on Mars include robust rough terrain navigation, highly mobile locomotion, perception, planning, self-assessment, task autonomy, and safeguarding. The focus of this work element is to investigate these issues within the context of an innovative legged locomotion concept, shown in Figure 5, proposed by Carnegie Mellon University (CMU).

The state-of-the-art is:

- o Moderate mobility using wheeled locomotion
- o Video camera or laser scanner sensor based perception
- o On-road autonomous planning using above sensors

The technology needs include:

- o Investigation of legged locomotion offering greatly enhanced mobility
- o Fused video camera/laser scanner perception
- o Planning for natural Martian terrain navigation, including self-assessment
- o Safeguarding

5.7. Systems Integration

The focus of this work element will be on the requirements analysis for a family of manned and unmanned rovers and the definition of integration issues associated with an integrated testbed.

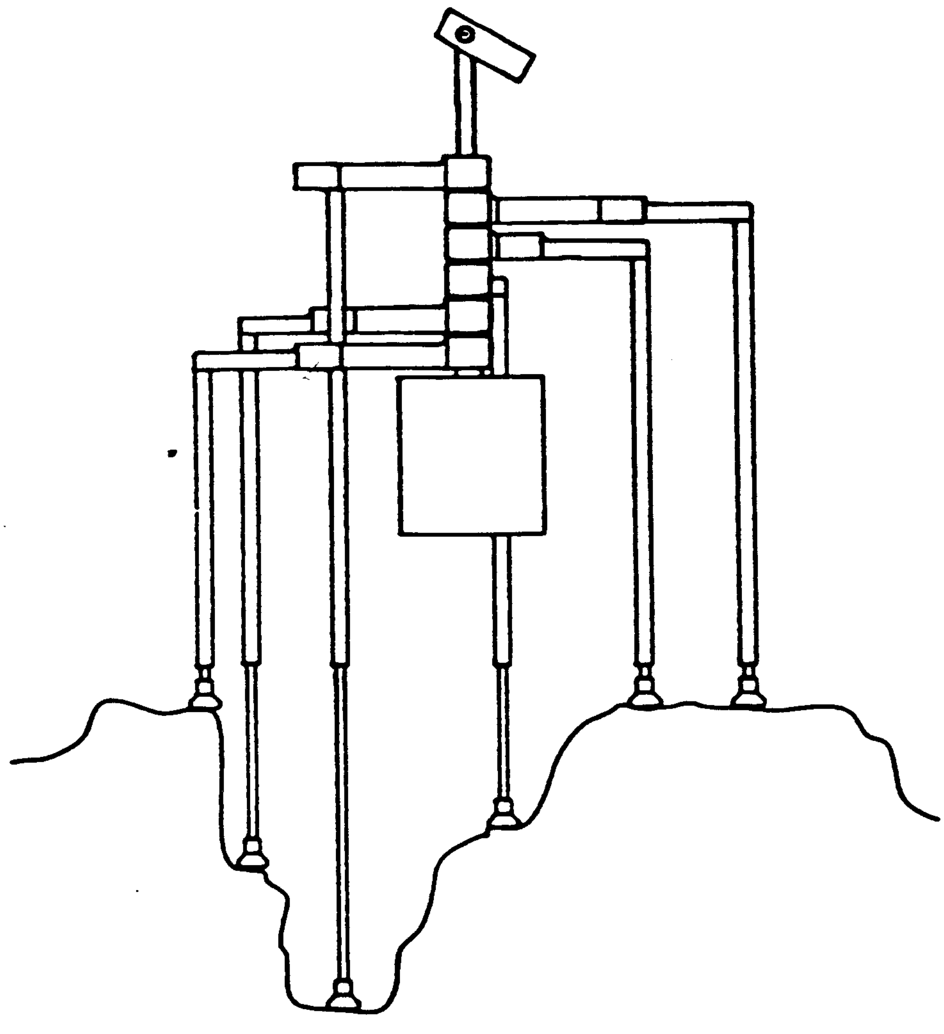


FIGURE 5. CMU LEGGED LOCOMOTION CONCEPT

Integration must begin early in the subsystem testbed design and once the testbed becomes operational, will continue to support evolving capability.

5.8. Thermal Control

A planetary rover requires an efficient thermal transfer and control system for maintaining rover elements within temperature limits for all environmental exposures, pre-launch through surface operation. Thermal energy storage may be required during aerocapture or during high power dissipation or adverse environmental conditions.

The state-of-the-art is represented by CRAF zero gravity two phase heat transfer loop and Air Force two phase thermal storage technology.

The technology needs include:

- o Assess the CRAF heat transfer loop technology relative to planetary surface gravity and other environmental conditions and develop breadboards as required
- o Assess the Air Force thermal storage technology relative to aerocapture and planetary surface gravity and other environmental conditions and develop breadboards as required.

5.9. Communications

A Ka-band (32 GHz) communication downlink (ie, from the planetary surface to earth) offers significant advantages compared to existing X-band (8.4 GHz) technology. These advantages include higher data rate, greater link reliability, smaller antenna size (important for packaging in the aeroshell as well as in the rover) and increased availability (eg, X-band communications from Mars would require the 70 meter DSN stations with a forecasted availability of 30% in the late 1990's as compared to 100% availability using Ka-band and the 34 meter DSN stations).

The state-of-the-art is:

- o Laboratory demonstrations of small monolithic millimeter arrays
- o X-band solid state and traveling wave tube (TWT) amplifiers
- o Ka-band TWT efficiency of about 20%

- o Commercial Ka-band field effect transistor(FET) power of about 0.15 W

The technology needs include:

- o A Ka-band monolithic transmitter phased array with over 100 elements producing 40 W of output power and greater than 30% overall DC to RF conversion efficiency
- o Millimeter wave integrated circuit (MMIC) digital data phased array signal distribution system
- o High DC to Rf conversion efficiency MMIC (40%) and TWT amplifiers (45%) operating at 32 GHz

5.10. Piloted Rover Technology

In order to maximize the usefulness of a manned lunar or Mars base, piloted surface transportation vehicles will be required. These vehicles would transport men and instrumentation to sites not within walking of the home base. Most likely, a number of different types of vehicles will be required, ranging from a short-range, man in life support suit, small-scale, lunar-type rover to a long-range, man in shirt sleeve environment, large-scale rover

The state-of-the-art is short range lunar-type rover technology

The technology needs include:

- o Design and trade studies should be conducted to formulate requirements, assess baselines and identify technology needs
- o Robotic systems for supplementing planetary surface manned extra vehicular activity (EVA)

5.11. Autonomous Mining/Construction Rover Technology

A manned lunar or Mars base will require unmanned (alleviating the need for manned surface EVA) utility rovers to carry out operations such as mining and construction. The complexities and demands on the limited manpower of a lunar or Mars base will require significant autonomy in order to enable safe, efficient and cost effective mining/construction operations.

The state-of-the-art is remote and teleoperated mining/ construction system technology.

The technology needs include:

- o Design and trade studies should be conducted to formulate requirements, assess baselines and identify technology needs
- o Aids to teleoperation
- o Autonomous system technologies for mining/construction

6. PROGRAM MANAGEMENT

This section describes the overall program management structure. It explains how an advisory working group supports the PPR and how significant interfaces between the NASA centers function. It delineates the process of program reviews and reporting. The PPR management organization is shown in Figure 6.

Overall direction and evaluation of the PPR is the responsibility of the Associate Administrator of the Office of Aeronautics and Space Technology (OAST). NASA Headquarters responsibility for this program has been assigned to the Director of the Information Sciences and Human Factors Division and NASA Center responsibility to the Technology and Applications Program at JPL.

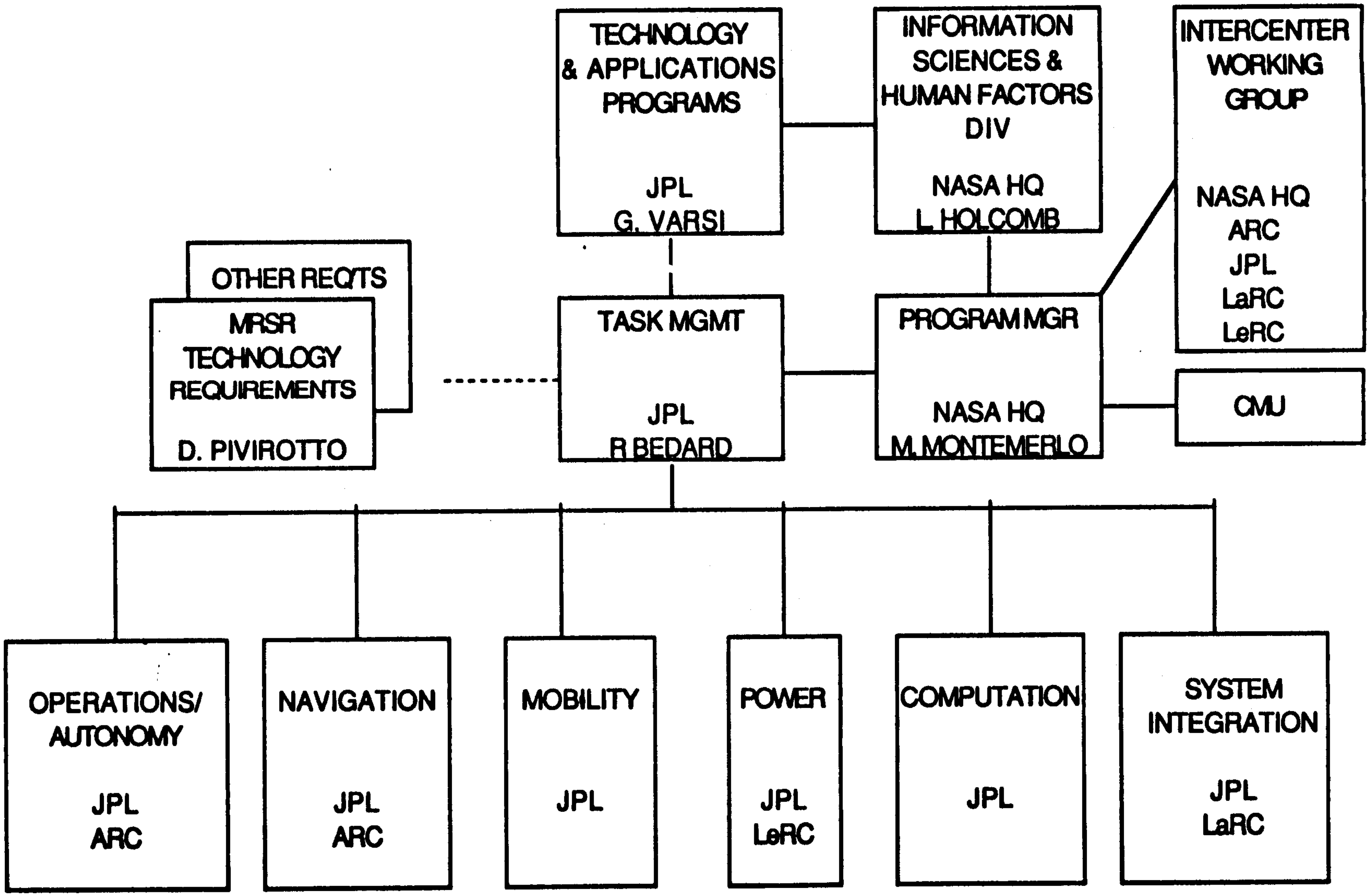
JPL has coordination and management responsibility for the implementation of the PPR program. The Director of JPL has assigned this responsibility to the Technology and Applications Program Office.

6.1. Organization

The PPR program at JPL is managed by the Manager of the Automation and Robotics Program within the Technology and Applications Program Office. The Manager of the JPL Automation and Robotics Program interfaces directly with the Director of the Information Sciences and Human Factors Division at NASA Headquarters, who receives NASA-wide management advice from the PPR Intercenter Working Group (IWG). The IWG assists in the definition, planning and progress review of the program. The members of the IWG are as follows:

- o Dr. Mel Montemerlo/NASA HQ (cochairman)
- o Mr. Roger Bedard/JPL (cochairman)
- o Mr. Dan Schyner/NASA HQ
- o Mr. John Mankins/NASA HQ
- o Mr. Don Rosenthal/ARC
- o Mr. John Bozek/LeRC

FIGURE 6. PATHFINDER PLANETARY ROVER MANAGEMENT



o Mr. Jack Hall/LaRC

Within OAST, Dr. Mel Montemerlo is the Program Manager and Mr. Dan Schyner is the Associate Program Manager with emphasis on the power related aspects of the PPR program.

Within JPL, a Task Manager has been assigned with overall responsibility for the technical, schedule and financial success of the PPR program. The task management responsibility has been assigned to Mr. Roger Bedard, who will report, within JPL, to Dr. Guilio Varsi, the Manager of the Automation and Robotics Program. The Program has been further broken down into the program elements as described in detail in the appendices.

Participating centers include JPL, ARC, LaRC and LeRC. All participating centers will be responsible to the NASA HQ Program Manager in OAST for all matters involving resources and program responsibility. They will be responsible to the lead center in matters pertaining to technical accomplishments, reporting, schedule and milestones.

6.2. Reviews

Quarterly program reviews will be conducted

6.3. Reporting

Quarterly reporting, per the OAST Civil Space Technology Initiative (CSTI) format, will be performed.

7. RELATED NASA AND DOD PROGRAMS

7.1. Pathfinder Sample Acquisition, Analysis and Preservation (SAAP)

The SAAP program, although a separate Pathfinder program, is closely related to the PPR program. The SAAP program will develop the technology required to identify, analyze and return to Earth scientifically valuable specimens from a planet's surface or near subsurface. Primarily, this program element will concentrate on methods for identifying and obtaining samples, techniques for performing physical, elemental and chemical analyses, and ways to process and contain the samples without contamination.

A close collaboration between the PPR and SAAP programs is absolutely necessary.

7.2. DARPA Autonomous Land Vehicle (ALV)

The Autonomous Land Vehicle (ALV) Program is sponsored by DARPA as part of its Strategic Computing (SC) program. The purpose of the SC Program is to advance the state-of-the-art in artificial intelligence, image understanding and advanced computer architectures and to demonstrate the applicability of these technologies to advanced military systems. The ALV project is one of the SC Program's application areas aimed at advancing and demonstrating the state-of-the-art of autonomous land navigation. The focus of this work has been on autonomous road following.

7.3. U.S. Army Robotic Vehicle Technology

The U.S. Army is sponsoring robotic vehicle technology development. While the principal focus of this work has been on teleoperation, the Tank Automotive Command (TACOM) has been sponsoring work at JPL on computer aided remote driving (CARD) technology.

8. COLLABORATION WITH OTHER AGENCIES/INDUSTRY/UNIVERSITIES

Significant collaborative efforts with other agencies, industry and universities are planned.

The Department of Defense (DOD), primarily through the Defense Advanced Research Projects Agency (DARPA) and the U.S. Army Tank Automotive Command (TACOM), are developing autonomous land vehicle technology. Significant synergy exists between autonomous rovers on earth and those on planets other than the Earth. The results of the DOD efforts will be used in the NASA Planetary Rover program. Moreover, it is the intent of the PPR to establish formal collaborative associations with the DOD program.

The Department of Energy (DOE), has the national charter to develop nuclear power technology. As described in the power element of the program, a RTG technology development responsive to planetary rover requirements is necessary. We intend to establish a formal relationship with DOE wherein NASA can secure DOE support for development of planetary rover RTG technology.

It is the intent of the PPR to contract with industry for those technology products which industry can best provide. In the first couple of years of the PPR, industrial contracting is expected in the areas of mobility modeling and control, power component development and data storage technology assessment.

A collaborative relationship with Carnegie Mellon University (CMU) will be established. CMU will develop an innovative legged-locomotion Mars Rover mobility prototype under a NASA grant which began in FY-88 and is expected to continue with FY-89 and 90 funding from the PPR line element. Possible ways of collaborating include forming a joint working group for selection of a common architecture, continuing this working group chartered to identify and capitalize on opportunities for technology transfer at functional capability level and exchange of personnel for extended periods of time.

9. SCHEDULE

The Pathfinder Planetary Rover Schedule is shown in Figure 7. The level 1 schedule milestones are described in Table 2. Level 2 schedules milestones are contained in the appendices

10. FUNDING

The Pathfinder Planetary Rover Program funding summary by program element from FY-89 thru FY-92 is shown in Table 3. A more detailed funding table which additionally shows the funding by NASA center is contained in Table 4. Funding at the work item level is contained in the appendices.

11. MANPOWER

The Pathfinder Planetary Rover Program manpower summary by program element, by NASA center, from FY-89 thru FY-92, is shown in Table 5. manpower at the work item level is shown in the appendices.

FIGURE 7 SCHEDULE MILESTONE PATHFINDER PLANETARY ROVER

ELEMENTS FY	89	90	91	92	93	REQUIREMENTS/GOALS
1. NAVIGATION	△1	△2	△3	△4	△5	o ROBUST CARD AND SEMI-AUTONOMOUS NAVIGATION
2. MOBILITY	△1	△2	△3	△4	△5	o VALIDATED 3-D MODEL FOR SIMULATION AND EXPECT-TATION GENERATION
3. POWER	△1	△2	△3	△4	△5	o DEVELOPED ENERGY SOURCE AND BREADBOARD ENERGY CONV/STORAGE/CIRCUITS
4. OPERATIONS/ AUTONOMY	△1	△2	△3	△4	△5	o VALIDATE HIGH LEVEL AND RAPID GROUND COMMAND GENERATION
5. COMPUTATION	△1	△2	△3	△4	△5	o DEVELOP BREADBOARD COMPUTER
6. ARCHITECTURE		△1				o DEMONSTRATE HIGH MOBILITY LOCOMOTION
7. SYSTEMS INTEGRATION		△1		△2		o VALIDATE EVOLVING INTEGRATED COMPONENT TECHNOLOGIES
8. THERMAL CONTROL 9. COMMUNICATION 10. PILOTED ROVER 11. AUTO MINING/CON'	PROGRAM ELEMENTS DO NOT BEGIN UNTIL FY-91 AND HAVE NOT BEEN PLANNED IN DETAIL AT THIS TIME					

TABLE 2. MILESTONES

Navigation

1.1. Complete development of SAN perception and planning algorithms and validate on the navigation testbed

1.2. Implement algorithms for expectation generation and sensor scheduling and test on the navigation testbed

1.3. Implement surface property determination sensors

1.4. Implement reactive planning and execution monitoring and validate on navigation testbed

1.5. Complete extensive testing of navigation algorithms in realistic terrains

Mobility

2.1. Complete preliminary definition of 3-D model requirements and a preliminary expectation generation model

2.2. Complete evaluation of 3-D analysis tools

2.3. Develop concept designs for mobility components including adaptive and highly efficient mechanical systems

2.4. Validate 3-D models with the mobility model testbed

2.5. Validate mobility mechanical systems in a testbed environment

Power

3.1. Finalize a NASA-DOE memorandum of agreement leading to the development of a modular RTG meeting MRSR requirements

3.2. Complete development of hot-pressed P type SiGe/III V

3.3. Complete breadboard advanced thermal/electric conversion with a Z of $0.85 \times 10^{-3}\ K^{-1}$

3.4. Complete smart switch PICs

3.5. Complete breadboard advanced battery and thermal/electric conversion with a Z of $1.4 \times 10^{-3}\ K^{-1}$

Operations/Autonomy

4.1. Complete preliminary definition of system executive requirements

4.2. Complete breadboard planning system integrating science and navigation planning

4.3. Complete interim breadboard system executive simulation (including both CARD and SAN modes)

4.4. Complete integrated science and navigation planning system with plan interruption, repair and splicing

4.5. Complete final simulation breadboard capability

Computation

5.1. Complete preliminary definition of requirements

5.2. Select preliminary architecture

5.3. Develop generic computation breadboard

5.4. Develop MRSR computation breadboard

5.5. Complete evaluation of MRSR breadboard

Architecture

6.1. Complete legged locomotion prototype rover vehicle

Systems Integration

7.1. Complete definition phase (integrated testbed functional requirements, functional design, risk assessment and class A cost estimate)

7.2. Complete integrated testbed validation in the outdoor test facility.

TABLE 3. PATHFINDER PLANETARY ROVER FUNDING SUMMARY

Program Element	FY-89	90	91	92	93
Navigation	1.028	2.4	4.5	4.5	4.7
Mobility	0.235	1.2	3.0	3.0	3.0
Power	0.440	4.0	4.7	6.6	6.9
Operations/Autonomy	0.528	0.9	1.5	1.5	1.8
Computation	0.196	0.8	3.0	4.0	3.0
Architecture(1)	2.000	3.0	-	-	-
System Integration	0.451	1.0	4.8	3.8	4.5
Thermal Control	-	-	-	1.0	1.0
Communications	-	-	-	2.0	2.0
Piloted Rover Technology	-	-	1.2	1.3	6.2
Auto Mining/Construction	-	-	-	1.0	3.4
Other(2)	0.060	0.7	1.3	1.3	1.5
TOTAL	4.938	14.0	24.0	30.0	38.0

(1) CMU Grant

(2) Includes associate administrator reserve, central scientific and technical ADP, wind tunnel and other facilities and small business innovative research (SBIR) set asides

TABLE 4. PATHFINDER PLANETARY ROVER FUNDING SUMMARY (ELEMENT FUNDING BY CENTER)

Program Element	FY-89	90	91	92	93
Navigation	**1.028**	**2.4**	**4.5**	**4.5**	**4.7**
JPL	1.028	2.0	4.0	4.0	3.7
Ames	-	0.4	0.5	0.5	1.0
Mobility -JPL	**0.235**	**1.2**	**3.0**	**3.0**	**3.0**
Power	**0.440**	**4.0**	**4.7**	**6.6**	**6.9**
JPL	0.440	3.4	4.0	6.1	6.2
Lewis	-	0.6	0.7	0.5	0.7
Operations/Autonomy	**0.528**	**0.9**	**1.5**	**1.5**	**1.8**
JPL	0.185	0.4	0.5	0.5	0.8
Ames	0.343	0.5	1.0	1.0	1.0
Computation-JPL	**0.196**	**0.8**	**3.0**	**4.0**	**3.0**
Architecture(1)	**2.000**	**3.0**	-	-	-
System Int	**0.451**	**1.0**	**4.8**	**3.8**	**4.5**
JPL	0.244	0.6	4.3	3.3	4.0
HQ Reserve	0.207	0.4	0.5	0.5	0.5
Thermal Control-JPL	-	-	-	**1.0**	**1.0**
Communications-JPL	-	-	-	**2.0**	**2.0**
Piloted Rover Tech(2)	-	-	**1.2**	**1.3**	**6.2**
Auto Mining/Const(2)	-	-	-	**1.0**	**3.4**
Other	**0.060**	**0.7**	**1.3**	**1.3**	**1.5**
SBIR	-	0.6	1.2	1.2	1.4
Other	0.060	0.1	0.1	0.1	0.1
TOTAL	**4.938**	**14.0**	**24.0**	**30.0**	**38.0**

(1) CMU Grant
(2) Center to be determined

TABLE 5. PATHFINDER PLANETARY ROVER MANPOWER SUMMARY (ELEMENT MAN-YEARS BY CENTER)

Program Element	FY-89	90	91	92	93
Navigation	**8**	**16**	**27**	**29**	**26**
JPL	8	15	26	28	25
Ames	0	1	1	1	1
Mobility -JPL	**1**	**5**	**10**	**11**	**12**
Power	**1**	**12**	**11**	**11**	**14**
JPL	1	9	8	9	12
Lewis	-	3	3	2	2
Operations/Autonomy	**3**	**4**	**6**	**6**	**6**
JPL	2	3	4	4	4
Ames	1	1	2	2	2
Computation - JPL	**2**	**5**	**14**	**16**	**12**
Architecture(1)	-	-	-	-	-
System Int	**3**	**7**	**9**	**8**	**7**
JPL	2	4	4	3	2
HQ Reserve	1	3	5	5	5
Thermal Control-JPL	-	-	-	**4**	**4**
Communications-JPL	-	-	-	**6**	**6**
Piloted Rover Tech(2)	-	-	**5**	**5**	**20**
Auto Mining/Const(2)	-	-	**0**	**6**	**9**
Other	-	-	-	-	-
TOTAL	**18**	**49**	**82**	**102**	**116**

(1) CMU Grant - No NASA or JPL manpower
(2) Center to be determined

APPENDIX - A. TECHNICAL WORK PACKAGES FOR NASA CENTERS

TABLE OF CONTENTS

A.1. AMES RESEARCH CENTER
A.1.1. Navigation - Explanation Based Model Revision and Uncertainty Management
A.1.2. Operations/Autonomy - Communicating Reasoning Systems

A.2. JET PROPULSION LABORATORY

A.2.1. Navigation
A.2.1.1. World sensing and Perception
A.2.1.2. Surface Property Determination
A.2.1.3. Route and Path Planning
A.2.1.4. Execution Monitoring

A.2.2. Mobility
A.2.2.1. Vehicle/Terrain 3-D Model
A.2.2.2. Deployable/Adaptable Structures

A.2.3. Power
A.2.3.1. RTG Technology
A.2.3.2. Thermal to Electric Conversion
A.2.3.3. Power Integrated Circuits
A.2.3.4. Lithium Disulfide Battery

A.2.4. Operations/Autonomy - Groundbased and Onboard Sequencing

A.2.5. Computation
A.2.5.1. General Purpose Computers
A.2.5.2. Special Purpose Computers
A.2.5.3. Data Storage

A.2.6. Systems Integration - Integrated Testbed and Task Management

A.3. LEWIS RESEARCH CENTER
A.3.1. Power - Sodium Sulfur Battery

A.1. AMES RESEARCH CENTER

A.1.1. NAVIGATION

TITLE: EXPLANATION BASED MODEL REVISION AND UNCERTAINTY MANAGEMENT

OBJECTIVE:

The primary objective of this work element is to develop a system which can revise models of the rover and its environment used for navigation and hazard avoidance. The system will require the capability to update the models as knowledge is acquired by experience and experimentation and as the success and failure of the rover's actions are observed over time.

A secondary objective of this work element is to support JPL in the area of uncertainty management, in general, but specifically in the navigation area (see JPL work item A.2.1.3.).

DESCRIPTION:

Bandwidth limitations and long round trip light times limit the amount and type of data that the rover will be able to send to Earth. In many, if not all situations, the rover will have a more complete description of its environment and the details of the effects of its actions on the environment, than will the operations staff on Earth. The rover must therefore have the ability to recognize significant differences between its models of itself and the environment and their actual states. In addition, the rover should be able to generate supportive information about these differences (eg, that speed of traverse over certain terrain is different from what is expected, and that it is due to the coefficient of friction over that terrain differing from the expected value).

TECHNICAL APPROACH:

The overall technical approach to be followed in this work item is primarily one of algorithm development followed by technology validation in the navigation testbed. Techniques to enable explanation based model revision for navigation and hazard avoidance will be developed. Development issues include:

- o Rover and world model representations
- o Using sensor input to check model validity
- o Validating differences between observed and expected data by explanation generation

ASSUMPTONS:

- o The navigation testbed is complete and available for use in the PPR program. No other facilities are required.
- o Funding estimates are in budget year dollars
- o Approximately 75% of the funding is contracted out

MILESTONES/SCHEDULE:

- o Complete brassboard explanation based model revision system (FY90)
- o Demonstrate capability to use sensor inputs (FY91)
- o Integrate model revision machine learning system into navigation testbed (FY92)
- o Test model revision machine learning system in navigation testbed (FY93)
- o Demonstrate increased robustness learning system (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	400	1
FY91	500	1
FY92	500	1
FY93	1,000	1

A.1. AMES RESEARCH CENTER

A.1.2. OPERATIONS/AUTONOMY

TITLE: COMMUNICATING REASONING SYSTEMS

OBJECTIVE:

To develop and validate the technology for interacting communicating planning and reasoning systems and to incorporate constraint propagation with planning.

DESCRIPTION:

Interactions between the various planetary rover subsystems (ie, mobility, navigation, sampling, communication, etc) are complex and not predetermined. Technology development in the area of interacting planning systems offers the potential of maximizing the science return of the mission while assuring its safe conduct.

TECHNICAL APPROACH:

The overall technical approach to be followed in this work item is primarily one of requirements definition, algorithm development and technology validation in the integrated testbed. Requirements will be defined through collaboration with payload scientists. Techniques to enable planning systems to interact will be developed. Development issues include:

- o Plan interruption, repair and splicing
- o Mixed initiatives receiving goals from many sources
- o Temporal relations and constraints

ASSUMPTIONS:

- o The integrated testbed is implemented
- o Funding estimates are in budget year dollars
- o Approximately 75% of the funding is contracted out

MILESTONES/SCHEDULES:

- o Formulate a design reference mission (FY89)

- o Demonstrate a breadboard planning system integrating science and navigation planning (FY90)
- o Demonstrate a breadboard planning system incorporating plan interruption, repair and splicing and temporal factors (FY92)
- o Integrate an interacting planning system in the integrated testbed (FY 93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	343	1
FY90	500	1
FY91	1,000	2
FY92	1,000	2
FY93	1,000	2

A.2. JET PROPULSION LABORATORY

A.2.1. NAVIGATION

A.2.1.1. WORLD SENSING AND PERCEPTION

OBJECTIVE:

To develop and validate the technology for world sensing and perception in order to allow a semiautonomous planetary rover to plan and follow safe paths on planetary terrains.

DESCRIPTION:

World sensing provides the rover (or human operator) with knowledge about the surrounding environment. In order to plan or traverse a safe path, information about the terrain is required. The rover will sense the terrain with sensors and develop a model of its surroundings. This world model will be used by the path planning function (either on the rover or on Earth) to determine safe paths for rover traverse. The output of world sensing and perception is a three dimensional map model of the terrain in the vicinity of the rover.

TECHNICAL APPROACH:

The overall technical approach to be followed in this work item is primarily one of algorithm development and testing of those algorithms using the navigation testbed in realistic terrains. Algorithm development is required in the following four areas of world sensing and perception:

- o Sensing
- o Sensor Fusion
- o Terrain Representation
- o Terrain Matching

Sensing provides the raw range information necessary to identify obstacles and other terrain features in the vicinity of the rover. Reliable stereo correlation algorithms using two or more cameras will be developed. Sensor processing algorithms for generating range maps with few significant errors and minimal missing data points will also be developed

Sensor fusion combines the output of multiple sensors sampled at different times into a single world model. Techniques for integrating the outputs of stereo correlation, laser ranging and possibly other sensors (Eg., phased array sonar, millimeter wave radar, etc) will be developed. Development issues include management of conflicts from multiple sources and management of data with varying reliability and validity.

The terrain representation is the world model generated and maintained by world sensing. Algorithm development allowing easy world model updating as appropriate to meet the needs of dynamic sensor fusion, limited memory, orbital and local data bases and path planning will be developed.

Terrain matching is the matching of local rover sensed data with lower resolution orbiter data for position determination and path planning. Terrain matching algorithms will be developed.

ASSUMPTIONS:

- o The navigation testbed is complete and available for use in this program. No other facilities are required.
- o This work element will be responsible for integrating the algorithms and software from the other three navigation work elements
- o Testing will be performed in the arroyo adjacent to the JPL facilities
- o Funding estimates are in budget year

MILESTONES/SCHEDULES:

- o Develop stereo correlation algorithms and test on navigation testbed (FY89)
- o Incorporate laser ranger and/or other sensors on navigation testbed (FY91)
- o Develop sensor fusion algorithms and test on navigation testbed (FY92)
- o Develop algorithms for multiple representations of terrain regions for conflict/uncertainty management and test on navigation testbed (FY93)
- o Complete extensive testing of complete world sensing and perception system in a variety of realistic environments (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	563	4
FY90	700	5
FY91	1,200	10
FY92	1,000	7
FY93	1,700	11

A.2. JET PROPULSION LABORATORY

A.2.1. NAVIGATION

A.2.1.2. SURFACE PROPERTY DETERMINATION

OBJECTIVE:

To develop and validate the technology for a surface property determination system which allows knowledge about the surface properties for the terrain over which a rover will traverse on planetary surfaces

DESCRIPTION:

Properties of the planetary surface near the rover may be critical to path planning and traverse. Surface load bearing capacity and coefficient of friction may determine whether a region is safe to traverse. Unstable surfaces may be common on planets such as Mars, for example, due to reduced seismic and erosional forces compared to Earth (unstable rock piles or thin crusted volcanic surfaces may remain for long periods of time without quakes or storms to dislodge or weather them). Visual or multispectral inspection, mechanical probes and other sensors may be used to measure surface properties near the rover.

TECHNICAL APPROACH:

Reliable surface property determination capability, both contact (ie, penetrators, sensor fitted vehicle wheels, etc) and non-contact (ie, radar, acoustic, etc) will be developed, specifically:

- o Sensor suites, both contact and non-contact, needed for surface property determination, and for the navigation testbed in particular will be defined. This study will identify appropriate sensors and assess the state-of-the-art of those sensors; this will determine whether technology development programs will be necessary to ensure technological readiness. For purposes of this plan, we have assumed that no new sensor technology development is required.

- o A sensor suite for implementation on the navigation testbed will be selected and procured (or availability for use during testing, if too costly)
- o Correlations between contact and non-contact sensor readings will be developed
- o Algorithms for autonomous correlation and data base update will be developed
- o Heuristic guides for determining when non-contact sensor readings imply contact sensing should be performed will be developed
- o Approaches and combinations of approaches will be tested extensively in realistic terrains with a variety of surface properties. Also, surface property analysis strategies will be tested under the same realistic conditions
- o The algorithms will be modified and improved in response to testing results

ASSUMPTIONS:

- o The navigation testbed is complete and available for use in this program. No other facilities are required.
- o Due to funding limitations, the efforts in this work item do not begin until FY90
- o Funding estimates are in budget year dollars

MILESTONES/SCHEDULES:

- o Define navigation testbed sensors (FY90)
- o Implement surface property determination sensors on navigation testbed and complete initial testing collecting sensor readings from a variety of realistic terrains (FY91)
- o Complete extensive testing in realistic terrains (FY93)

BUDGET

Year	Funding(K$)	Manpower(Wk-Yrs)
FY89	0	0
FY90	300	2
FY91	800	5
FY92	1,000	7
FY93	400	4

A.1. JET PROPULSION LABORATORY

A.2.1. NAVIGATION

A.2.1.3. AUTONOMOUS ROUTE/PATH PLANNING

OBJECTIVE:

To develop and validate the technology for:

- o Automatically generating (on Earth) rover traversable routes from one site to the next (one to tens of kilometers) from orbiter image data
- o Automatically generating safe paths (onboard rover) for traversing next path segment (several to tens of meters) from rover onboard sensing

DESCRIPTION:

Route and path planning functions are responsible for identifying and selecting safe and desirable paths through the immediate and distant terrain around the rover vehicle. The process is autonomous insofar as the selection of waypoints towards a goal location and hazard avoidance are performed with minimal or without human control. These functions use the output of the sensing and perception and the surface property determination systems.

Earth-based global route planning is a critical component of ground operations and mission planning. It must be efficient in order to minimize command sequence turnaround time and it must be fully integrated with the local navigation system.

Onboard path planning is necessary to reduce ground communications to a level consistent with mission objectives

The task will focus on technology which can:

- o Handle large data bases (>Mbyte)
- o Be used in outdoor, natural environments without man-made obstacles
- o Plan paths around geometric and surface property obstacles

- o Handle considerable uncertainty in sensing and perception data, terrain maps and vehicle locating ability
- o Plan routes that take into account execution monitoring constraints
- o Replan in the face of new data
- o Function with or without the assistance of humans in planning incremental paths through difficult, long distance traverses

TECHNICAL APPROACH:

The overall technical approach to be followed on this work item is primarily one of algorithm development and technology validation using the navigation testbed in realistic terrains. The key features of the route/path planning algorithms include:

- o Integrated hierarchal terrain model
- o Terrain features modeled at different levels of detail
- o Traverse cost modeled as links between different parts of the data base
- o Search heuristics used to efficiently search through the large data base
- o Path calculated using energy costs, path accuracy, safety estimate and probability of need to replan
- o Replan incrementally at different levels of detail

Route/path planning algorithm development is required in the following five areas:

- o Path Planning Algorithms
- o Local Navigation and Control
- o Uncertainty Management (ARC will support this item - see A.1.1.)
- o Terrain Representation (see work item A.2.1.1.)
- o Massive Data Bases

Algorithms for the identification, generation and selection of acceptable paths for a rover over planetary surfaces will be developed. Development issues include:

- o Robust local hazard avoidance
- o Incremental route planning
- o Global/local path planning at multiple levels of resolution
- o Path planning with coordinated use of multiple terrain models

Algorithms for the management of possibly many heterogenous computing procedures in the service of local navigation and control will be developed. Development issues include:

- o Management of planning and world sensing and perception/surface property determination system interactions
- o Autonomous assessment of path risk
- o Multi-factor path optimization

Algorithms for enabling robust path planning with incomplete and/or errorful data will be developed. Development issues include:

- o Management of positional uncertainty
- o Uncertainty in terrain/surface models
- o Planning for dynamic sensing to resolve uncertainty in terrain models
- o Robust path planning with degraded terrain knowledge bases and sensor data

Algorithms for enabling path planning functions to take advantage of a wide variety of data about the terrain is required. Development issues include:

- o Geometric representations of terrain at multiple resolutions
- o Combined geometric and surface property representation

Algorithms to create, maintain and utilize massive terrain knowledge bases for rover path planning will be developed. Development issues include:

- o Reliable creation of massive data bases
- o Efficient dynamic update and revision of data bases
- o Support for robust path planning using multiple models
- o Efficient search through massive data bases

ASSUMPTIONS

- o The navigation testbed is complete and available for use in this program. No other facilities are required.
- o The funding estimates are in budget year dollars

MILESTONES/SCHEDULES:

- o Implement preliminary hazard avoidance path planning algorithms and test on navigation testbed (FY89)
- o Implement incremental route planning algorithms and test on navigation testbed (FY90)
- o Implement global/local path planning at multiple resolution algorithms and test on navigation testbed (FY91)
- o Implement robust hazard avoidance path planning algorithms and test on integrated testbed (FY92)
- o Complete extensive testing in realistic terrains (FY93)

BUDGET

Year	Funding(K$)	Work-Years
FY89	196	2
FY90	500	4
FY91	1,000	8
FY92	1,000	7
FY93	800	5

A.1. JET PROPULSION LABORATORY

A.2.1. NAVIGATION

A.2.1.4. EXECUTION MONITORING AND REPLANNING

OBJECTIVE:

To develop and validate the technology for:

- o Performing semi-dynamic simulations of rover traverses onboard the rover in real time
- o Automatically monitoring rover traverses, in real time, to ensure vehicle safety
- o Enabling rover vehicle to take corrective action as necessary

DESCRIPTION:

Execution monitoring and replanning functions are responsible for the continual verification of the health and status of the vehicle, the progress of planned vehicle operations and for determining any response to unforeseen, anomalous or dangerous conditions during vehicle operation. Execution monitoring and reactiveness are necessary for vehicle safety.

TECHNICAL APPROACH:

The overall technical approach to be followed in this work item is primarily one of algorithm development and technology validation using the navigation testbed in realistic terrains. Algorithm development is required in the following three areas:

- o Execution Monitoring
- o Explanation Based Model Revision (this item is being performed by ARC - see A.1.1.)
- o Terrain and Vehicle Modeling (see work item A.2.4.1.)

Algorithms to plan sensor utilization, generation of expectations and real-time assessment of vehicle performance during path traverse will be developed. Development Issues include:

- o Modeling of sensor events during path traverse

- o Expectation generation using vehicle kinematics and dynamics
- o Expectation generation using vehicle and terrain surface models
- o Analysis and comparison of partial and uncertain sensor data with expectations of vehicle performance
- o Anomaly prediction and avoidance

The explanation based model revision work item is being performed by Ames Research Center. See work element A.1.1. for a description of this work.

The interpretation of data from onboard sensors requires models of the vehicle and its environment. These models are being developed under the mobility program 3-D modeling work element. See work item A.2.4.1. for a description of this work.

ASSUMPTIONS

- o The navigation testbed is complete and available for use in this program. No other facilities are required.
- o The funding estimates are in budget year dollars

MILESTONES/SCHEDULES:

- o Implement preliminary algorithms for execution monitoring (FY89)
- o Implement algorithms for expectation generation with sensor scheduling and test on navigation testbed (FY90)
- o Implement algorithms for expectation generation using vehicle/surface models and test on navigation testbed (FY91)
- o Implement algorithms for reactive planning and execution and test on navigation testbed (FY92)
- o Complete extensive testing in realistic terrains (FY93)

BUDGET

Year	Funding(K$)	Work-Years
FY89	269	2
FY90	500	4
FY91	1,000	8
FY92	1,000	7
FY93	800	5

A.2. JET PROPULSION LABORATORY

A.2.2. MOBILITY

A.2.2.1. VEHICLE/TERRAIN 3-D ANALYSIS TOOL

OBJECTIVE:

To develop and validate an analytical tool for modeling 3-dimensional vehicles moving over general terrain in order to support:

- o Vehicle design and simulation
- o Controls prototyping, design and testing
- o Local navigation simulation and expectation planning

DESCRIPTION

Key characteristics that are needed in a vehicle/terrain model include:

- o A general terrain model that represents wide range of possible soil types and couples with the vehicle model
- o Tools for analysis of the interaction of the vehicle with general terrain
- o Terrain/vehicle interaction at slow speeds involving soil deformation, traction/slip and flexible body dynamics for determining obstacle climbing capability
- o Non-linear, large displacement formulation for an elastic vehicle/drive element on arbitrary terrain at any angle of attack
- o Integrated or coupled design, controls and simulation capabilities

TECHNICAL APPROACH

The overall technical approach to be followed in this work element is as follows:

- o Develop the functional, performance and interface requirements of the needed analysis tools
- o Identify critical analyses that must be performed to develop and verify vehicle and control designs

- o Develop terrain and surface property model
- o Evaluate general/special purpose codes for ability to meet requirements
- o Develop/augment formulation, algorithms and code (and perform a make or buy decision to determine whether this should be contracted out or developed in-house)
- o Validate the model through comparison and correlation with test results (ie, the mobility model validation testbed and the navigation and integrated testbeds)

ASSUMPTIONS:

- o Funding estimates are in budget year dollars
- o Manpower estimates assume model development in concert with industry contractor(s)

MILESTONES/SCHEDULES

- o Develop preliminary modeling requirements (FY89)
- o Develop preliminary expectation generation model (FY89)
- o Develop model validation testbed (FY90)
- o Evaluate general/special purpose codes for ability to meet requirements. Finalize make or buy decision (FY90)
- o Develop 'tire/terrain' interaction model (FY91)
- o Develop/augment formulation and algorithms (FY91)
- o Develop code and complete code testing (FY 92)
- o Validate model with mobility model testbed results (FY92)
- o Validate model with navigation and integrated testbed results (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	235	1
FY90	1000	3
FY91	800	2
FY92	400	3
FY93	400	2

A.2. JET PROPULSION LABORATORY

A.2.2. MOBILITY

A.2.2.2. MOBILITY COMPONENTS

OBJECTIVE:

To develop technologies for locomotion elements (eg, wheels) that include deployable/adaptive mechanical systems which can accommodate unknown terrain conditions and mission constraints and to develop high efficiency drive, articulation and control component technologies that will allow the rover to adapt itself to changing conditions within limited rover resources

DESCRIPTION

The widely varying terrains and the different rover operational states (ie, traverse, sampling, communicating) may require adaptive mechanical system technologies for wheels, suspensions and structural elements. For example, vehicle flexibility may be desired for traversing rough terrain whereas a rigid platform may be required for sampling operations. Active structure concepts may be required to provide changes in geometry, stiffness and/or damping.

Deployable structure concepts and technologies which allow for packaging factors of 10 to 1 may be desired. Large wheels are more terrain insensitive, but aeroshell volume may limit the available volume for rover storage.

Drive, articulation and control components may be required for locomotion, steering, suspension geometry changes, self-righting capability, etc. These devices may be required to operate for extended periods in a hostile environment. High performance ,high efficiency, long life device technologies which can operate on a planetary surface are required.

TECHNICAL APPROACH

The overall technical approach to be followed in this work item is as follows:

- o Identify specific mobility technology requirements using the results of the MRSR design studies
- o Investigate concepts and materials using the vehicle/terrain analysis model
- o Develop brassboard designs
- o Validate designs in a testbed environment

ASSUMPTIONS:

- o Due to funding limitations, this work element does not begin until FY90
- o Funding estimates are in budget year dollars
- o Most development work is assumed to be contracted to industry

MILESTONES/SCHEDULES:

- o Identify technology requirements(FY90)
- o Develop component technology concepts (FY91)
- o Develop brassboards (FY92)
- o Integrate into testbeds and validate designs (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	200	2
FY91	2,200	8
FY92	2,600	8
FY93	2,600	8

A.2. JET PROPULSION LABORATORY

A.2.3. POWER

A.2.3.1. RTG TECHNOLOGY

OBJECTIVES:

To develop radioisotope thermal generation (RTG) heat source technology applicable to planetary rover surface operations.

DESCRIPTION

The Deptartment of Energy (DOE) Modular RTG program is the only funded space power heat source program at power levels applicable to unmanned planetary rovers (ie 0.5-1.0 KWe). This program is developing RTG technology for operation in the spacecraft operation in the vacuum of space. This technology, however, is not compatable with operation in the atmosphere of a planetary surface nor with the expected rover dynamic/thermal environments. Without NASA intervention, a rover RTG will not be available.

TECHNICAL APPROACH

The overall approach is to define the planetary rover RTG requirements and establish a formal relationship with the DOE wherein NASA can secure DOE support in RTG technology responsive to the planetary rover requirements. This relationship must necessarily be formed at high managerial both within NASA and DOE. The PPR program will monitor the activity leading to the formalization of this relationship.

ASSUMPTIONS:

- o The DOE will fund the required rover RTG technology

MILESTONES/SCHEDULES

- o Finalize a NASA-DOE memorandum of agreement leading to the development of a modular RTG meeting MRSR requirements (FY89)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	0	0
FY91	0	0
FY92	0	0
FY93	0	0

A.2.3.2. THERMAL TO ELECTRIC CONVERSION

OBJECTIVES:

To develop a solid state thermal to electric conversion system compatible with, and able to be integrated into, the DOE Modular RTG development program and to demonstrate solid state converter technology that provides the following performance characteristics:

- o Conversion efficiency of > 14% at 1300K hot junction
- o Reproducible Z's of 1.4 X $10^{-3}K^{-1}$

DESCRIPTION

Solid state thermoelectric conversion is based upon the Seebeck effect whereby a voltage is produced along a temperature gradient in a material and across a junction between dissimilar materials. The state-of-the-art of high efficiency thermoelectric generators consists of either multiple single or modular thermocouples arranged around a suitable heat source. The active thermoelectric material is composed of N and P doped semiconductors along with a heat collector at a hot junction and a cold side heat exchanger to enhance the thermal gradient across the thermocouples.

TECHNICAL APPROACH

The overall technical approach is to generate and conduct a 5 year materials development program for advanced silicon germanium (SiGe) alloys. JPL will focus efforts on crystal growth, dopant optimization and model development. Industry will perform the development of hot-pressed SiGe materials. Theoretical analyses will be performed at JPL and in universities. There will be a continuous interaction between industry, universities and JPL. This effort involves an evaluation of both N-type and P-type materials and will be conducted in two phases. The first phase (2 years) will result in a SiGe/GaP (Gallium Phosphide) material with a combined Z of about 0.85 X $10^{-3}k^{-1}$ as a goal. The second phase (3 years) will analyze SiGe/III-V alloys with a goal of a combined Z of greater than 1.4 X $10^{-3}k^{-1}$.

ASSUMPTIONS:

- o Funding estimates are in budget year dollars
- o The cooperative funding and synergism between the NASA Research and Technology (R&T) base in FY 89 and the SP-100 Programs in all years are maintained and continued
- o A mechanism is developed between NASA and the DOE to feed and coordinate MRSR RTG requirements into the DOE isotope power planning and development process
- o A synergistic and cooperative thermal to electric conversion system development is put in place between JPL, DOE and NASA
- o There is a funding base within the DOE to take the MRSR requirements and provide RTG's for the MRSR mission elements
- o This program will provide an improved thermoelectric material that can be implemented into a MRSR unique Mod RTG; however, this program will not provide that implementation
- o The MRSR system engineering and design team activities remain synergistic with and feed requirements to the RTG development effort
- o The RTG power source developments remain separate from any rover testbed activities
- o Funding for Electrically Heated Thermoelectric Generators (ETG) to support MRSR system testbeds is provided separately

MILESTONES/SCHEDULES

- o Initiate crystal growth and binary doping of N and P-type materials (FY89)
- o Kickoff contracts with industry to develop hot-pressed P-type SiGe/III-V (FY89) (assumes SP-100 funding on N-type materials)
- o Optimum dopants determined and a P-type electrical/thermal model developed (FY90)
- o Demonstrate a combined Z of 0.85 X $10^{-3}k^{-1}$ (FY91)
- o Initiate theoretical studies and crystal growth/doping of advance SiGe (FY91)
- o Manufacture prototype multicouple material and initiate accelerated life testing (FY92)
- o Model of advanced SiGe developed (FY92)
- o Demonstrate a combined Z of 1.4 X $10^{-3}k^{-1}$ and initiate accelerated life testing (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	440	1
FY90	1,400	8
FY91	2,400	8
FY92	2,500	8
FY93	2,200	8

A.2. JET PROPULSION LABORATORY

A.2.3. POWER

A.2.3.2. POWER INTEGRATED CIRCUITS

OBJECTIVE:

To develop the technology necessary to achieve power densities of 0.5 W/cm^3 for Rover Power Management and Distribution (PMAD) functions and to demonstrate solid state Power Integrated Circuits (PICs) offering the following characteristics:

- o Minimize the mass of PMAD per unit power handled from 8.3 to to 4.8 kg/100 W
- o Increase power of power switching/control elements from 0.06 to 0.5 W/cm3

DESCRIPTION

Power Integrated Circuit (PIC) technology is the technology whereby power analog circuitry and signal processing control logic is integrated onto the same substrate, yielding a unified, monolithic device. PICs will allow Rover power systems to become smaller, more lightweight, less costly, and more reliable while maintaining high efficiency. PICs enable distributed PMAD topology operating from a single power bus. This significantly reduces cabling mass and permits integration of electrical and thermal control functions.

TECHNICAL APPROACH:

The overall technical approach is to establish an industrial technology base capability for the manufacture of flight quality PIC devices. A first step in the progression of increasing complexity building block functions is the development of a smart switch integrating low power signal processing circuitry with high power low loss switches. The next level of complexity is the smart pole. Integration of two smart switches into the same structure doubles the complexity, but quadruples the available applications. Finally, the most general building block is the smart interface device that will utilize all of the above developments and add optoelectric control to enable distributed power control. Its components will include smart switches, smart poles, miniaturized transformers, optical comand and telemetry encoders/decoders, optoelectric converters and protection circuitry within the same package.

ASSUMPTIONS:

- o Funding estimates are in budget year dollars
- o The MRSR system engineering and design team acyivity remains synergistic with and feeds requirements to the PIC PMAD concept
- o Funding for PIC PMAD power testbeds and Rover system testbed materials is provided from other sources

MILESTONES:

- o Initiate interaction with several selected manufacturers of power chips to develop a low level PIC technology base. Perform the preliminary development of monolithic sensors and synchronous rectifiers (FY90)
- o Finalize the designs for a smart switch PIC at two manufacturers and conduct performance evaluations on the delivered products (FY91)
- o Begin the development and fabrication planning for the smart pole device. Develop the techniques for monolithic current and temperature sensing and transfer this technology to industry (FY91)
- o Complete the design and fabrication for the smart pole device and perform evaluation testing of the delivered products (FY93)
- o Develop the techniques for optoelectric/analog integration and transfer this technolgy to industry for smart interface device preliminary design (FY93)
- o Complete the design and fabrication for the smart interface device and perform evaluation testing of the delivered products (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	900	4
FY91	800	3
FY92	1,800	5
FY93	2,000	7

A.2. JET PROPULSION LABORATORY

A.2.3. POWER

A.2.3.1. LITHIUM TITANIUM DISULFIDE BATTERY

OBJECTIVES:

To develop the technology necessary to increase the energy density, provide longer active shelf life and reduce the self discharge rate of an energy storage device for a planetray rover and to demonstrate an advanced lithium rechargeable battery technology having the following characteristics:

- o Specific energy of 100 watt-hrs/kg
- o Cycle life of1000 cycles at a 50% depth-of-discharge

DESCRIPTION

This work element will provide the technology base for advanced electrochemical energy storage systems required to support the MRSR mission application. The electrochemical system selected is an ambient temperature rechargeable lithium anode based system with a projected life of 1000 cycles and a specific energy of 100 watt-hrs/kg. Characteristics required for these applications include higher energy densities (lower mass and volume), increased rate capability, safety in a battery configuration, long activated storage life and simplified charge control methods.

TECHNICAL APPROACH

The overall technical approach is to establish an industrial technology base capability to manufacture flight quality Lithium Titanium Disulfide (Li-TiS_2) cells. Materials selection for high quality electrode and electrolyte as well as development of fabrication processes for these components will be accomplished. This strategy will begin with a small cell design/ development effort. Once these processes and cells have been optimized and evaluated, a larger cell size (targeted for MRSR) will be taken through development in the same manner.

ASSUMPTIONS:

- o Funding estimates are in budget year dollars
- o MRSR system engineering and design team activities remain synergistic with and feed requirements to this energy storage concept
- o Funding for power testbed and MRSR system testbed materials are provided separately

MILESTONES/SCHEDULES:

- o Initiate interaction with selected cell manufacturers to develop cell component candidate materials and manufactuiring processes for 5 Amp-hr lithium cells (FY90)
- o Optimize 5 Amp-hr cell design and fabrication (FY91)
- o Conduct a performance evaluation leading to a demonstration of 500 cycles at the C/3 (capacity at 3 hour discharge)rate (FY91)
- o Scale up the technology base to a 35 Amp-hr cell size using component and cell engineering principles to demonstrate safe operation of the 35 Amp-hr cell (FY92)
- o Complete the design and fabrication processes for the 35 Amp-hr cells, initiating the development of a performance data base (FY93)
- o Complete characterization testing and demonstration of 100 watt-hr/kg with 1000 cycles of safe operation at the C/3 discharge rate (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	1,100	5
FY91	800	3
FY92	1,800	6
FY93	1,400	8

A.2. JET PROPULSION LABORATORY

A.2.4. OPERATIONS/AUTONOMY - GROUNDBASED AND ONBOARD SEQUENCING

OBJECTIVE:

To develop advanced, high level uplink command generation tools for improving the capability of groundbased sequence integration teams and for minimizing the downlink data interpretation/uplink command generation turnaround time and to develop a 'surrogate' sequence integration team onboard the rover for autonomous operations.

DESCRIPTION:

An order of magnitude or more improvement in present uplink command generation turnaround time capability is needed for reasonable Mars Rover operation. The uplink command generation technology needed for Mars Rover operation is different from previous technology developed at JPL. The Mars Rover is a spacecraft on wheels/legs which must operate within a more complex and unknown environment than conventional spacecraft. In addition, Mars Rover operation must be adaptive in that downlink data will influence the uplink command generation process in a more profound way than with conventional spacecraft.

TECHNICAL APPROACH:

Due to the newness of developing ground-based and high level onboard command generation tools for planetary rovers, it must be recognized that the approach can only be stated in a generic fashion at this time. The development steps are as follows:

- o Determine requirements
- o Evaluate state-of-the-art
- o Develop technologies for efficient and rapid uplink/onboard command generation turnaround time including the appropriate level of automated:
  - goal directed sequence planning
  - sequence scheduling
  - plan simulation
  - subsystem feedback interpretation
  - plan execution monitoring and analysis

- failure analysis
- fault protection
- fault recovery

o Prototype the ground-based/onboard operations software

Rapid software prototyping using a breadboard environment will be utilized. Actual sequence generation software would be funded and performed for specific projects such as MRSR.

ASSUMPTONS:

o Development schedules and budgets require integrated technology development of ground-based and onboard sequencing capabilities
o Target compute power will not require assembly language development and packing of software into onboard processor
o Automated science developments are being covered by the Pathfinder SAAP Line item and the Ames effort described in Section A.1.2.
o Funding estimates are in budget year dollars

MILESTONES/SCHEDULES

o Develop preliminary requirements and evaluate state-of-the-art (FY89)
o Complete preliminary rover system executive simulation (FY 90)
o Complete interim simulation capability including operations in both CARD and SAN modes (FY91)
o Complete final simulation capability (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	185	2
FY90	400	3
FY91	500	4
FY92	500	4
FY93	800	5

A.2. JET PROPULSION LABORATORY

A.2.5. COMPUTATION

A.2.5.1. GENERAL PURPOSE COMPUTING

OBJECTIVES:

To develop and validate the technology to enable general purpose, fault tolerant, fast processing speed, low power consumption, low mass, space qualified computers.

DESCRIPTION

Onboard general processing computers are required for functions such as:

- o Adaptive vehicle control
- o Local navigation
- o Global navigation
- o Route planning
- o Robotic arm sample acquisition system control
- o Science planning
- o Science data analysis and acquisition
- o Science data handling
- o Fault protection
- o Command sequencing
- o Telemetry
- o Power management
- o Housekeeping

From JPL past experience on spacecraft projects and the premise for any future mission is that mission capabilities will be limited by the performance of its onboard computer. Thus it behooves the computer developers to maximize computer capability within the current state-of-the-art. The computer technology issues are threefold; namely:

- o System design (architecture)
- o Hardware design

o Software design (operating system and tools)

Given that planetary rover computing resources must be shared (ie, for navigation, science, thermal control, power management, etc), a computer architecture with distributed resources seems to be the most practical architecture.

TECHNICAL APPROACH

- o Perform a requirements study to assess Mars Rover computation needs and compare to available computer technology
- o Perform a feasibility study to look at algorithms and sizing of processor, identify candidate architectures and develop supporting rationale.
- o Perform optimization studies based on candidate architectures and typical algorithms
- o Evaluate selected general computer system on generic parallel computer breadboard
- o Design and fabricate a Mars Rover breadboard system including software operating system and support environment
- o Evaluate the Mars Rover breadboard system

ASSUMPTIONS:

- o Funding estimates are in budget year dollars

MILESTONES:

- o Define preliminary requirements (FY89)
- o Select preliminary architecture (FY90)
- o Optimize with generic breadboard evaluation(FY91)
- o Design and fabricate Mars Rover breadboard (FY92)
- o Compete evaluation of Mars Rover breadboard (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	98	1
FY90	400	3
FY91	1,400	8
FY92	2,000	10
FY93	1,800	8

A.2. JET PROPULSION LABORATORY

A.2.5. COMPUTATION

A.2.5.2. SPECIAL PURPOSE COMPUTING

OBJECTIVES:

To develop and validate the technology to enable special purpose, fault tolerant, fast processing speed, low power consumption, low mass, space qualified computers for special purpose functions such as for image processing for semiautonomous navigation.

DESCRIPTION

An onboard image processing architecture with the following characteristics is required:

- o Several hundred MIPS performance
- o Adaptable to a set of special purpose processing algorithms needed for SAN such as:
    - stereo image correlation
    - terrain matching
    - feature extraction
    - slope computations
- o Flexible to changing requirements
- o Reliable over mission lifetime
- o Fault tolerant
- o Power/mass/volume efficient
- o Space flight qualifiable

TECHNICAL APPROACH

- o Perform a requirements study to assess Mars Rover special purpose computation needs and compare to available computer technology
- o Perform a feasibility study to look at algorithms and sizing of processor, identify candidate architectures and develop supporting rationale.
- o Perform optimization studies based on candidate architectures and typical algorithms

- o Design and fabricate a Mars Rover breadboard system including software operating system and support environment
- o Evaluate of Mars Rover breadboard system

ASSUMPTIONS:

- o Funding estimates are in budget year dollars

MILESTONES:

- o Evaluate candidate sensors and processing algorithms and programs(FY90)
- o Define functional and performance requirements (FY91)
- o Select special processor architecture(FY91)
- o Design and fabricate a Mars Rover breadboard (inc software) (FY92)
- o Compete evaluation of the Mars Rover breadboard (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	200	1
FY91	1,000	5
FY92	1,000	5
FY93	600	3

A.2. JET PROPULSION LABORATORY

A.2.5. COMPUTATION

A.2.5.3. DATA STORAGE

OBJECTIVES:

To develop and validate the technology to enable high performance data storage capability.

DESCRIPTION

An onboard data storage system with the following characteristics is required:

- o Supports diverse processing functions
- o Tens of gigabits of storage capacity
- o Tens of megabits per second input/output rates
- o Random access and non-volatile
- o Reliable over mission lifetime
- o Power/mass/volume efficient
- o Space flight qualifiable

TECHNICAL APPROACH

- o Perform a requirements study to assess Mars Rover data storage needs and compare to available technology
- o Perform a feasibility study to look at candidate architectures and develop supporting rationale.
- o Perform optimization studies based on candidate architectures
- o Design and fabricate a Mars Rover breadboard system
- o Evaluate Mars Rover breadboard system

ASSUMPTIONS:

- o Funding estimates are in budget year dollars

MILESTONES:

- o Evaluate candidate storage techniques, architecture and programs(FY89)
- o Define functional and performance requirements (FY90)
- o Select data storage architecture(FY91)
- o Design and fabricate a Mars Rover breadboard (inc software) (FY92)
- o Compete evaluation of the Mars Rover breadboard (FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	98	1
FY90	200	1
FY91	600	1
FY92	1,000	1
FY93	600	1

A.2. JET PROPULSION LABORATORY

A.2.6. SYSTEMS INTEGRATION - TASK MANAGEMENT, SYSTEMS ANALYSIS AND INTEGRATED TESTBED

OBJECTIVES:

The objective of the task management work element is assure the successful accomplishment of the Pathfinder Planetary Rover program technical, schedule and financial goals.

The objective of the systems analysis work element is to define requirements and technology needs for a family of rovers, both manned and unmanned, for exploration, science, mining, construction and cargo handling on lunar and planetary surfaces.

The objective of the integrated testbed program. element is to provide for a testbed facility in order to validate the subsystem technology in a meaningful way.

DESCRIPTION:

Since JPL is the lead center, the Task Manager is responsible for coordinating all PPR work elements (ie, including those performed by other NASA centers as well as universities) in support of the NASA HQ Program Manager. In addition, the Task Manager is responsible for coordinating with the MRSR Rover Preproject Office to assure that developing technology requirements are addressed within the context of the PPR program.

A family of rovers will be required for future NASA mannned and unmanned missions to lunar and planetary surfaces. This systems analysis effort will address key issues such as:

- o Missions to various lunar and planetary surfaces (Moon, Phobos, Mars, etc)
- o Short and long range manned and unmanned rovers
- o Pressurized and unpressurized manned rovers
- o Automated mining, construction amd cargo handling rovers

An integrated testbed facilty is needed in order to validate the technology being developed in the advanced subsystem technology elements of the PPR program. Key characteristics of the integrated testbed activity are as follows:

- o Integrated testbed definition would begin in FY89 and continue thru FY90. Testbed definition includes functional requirements, functional design, risk assessment and cost estimates.
- o Integrated testbed implementation would begin in the FY-91 time frame
- o The integrated testbed implementation team would be separate and distinct from the advanced technology development team - technology would be transferred to the implementation team from the subsystem technology team.
- o The integrated testbed would either be fully contracted or major subsystems contracted to industry
- o Funding augmentation would be provided by the MRSR Preproject
- o The integrated testbed would include facilities for test and demonstration; possibly an indoor (1/4 acre size) and an outdoor (10's of kms) facility. The indoor facility would support mobility characterization and local path planning and execution testing. It would have controlled terrain (obstacles, crevasses, slopes, etc) and controlled environment (lighting, atmosphere, etc). the outdoor facility would support global route planning and navigation and would be a digital proving ground.

APPROACH:

The basic task management approach is one of:

- o Planning
- o Monitoring actual progress relative to plan
- o Initiating corrective action as required
- o Communicating with all personnel in order to assure mutual expectations
- o Facilitate communication and collaboration between program elements as appropriate

The overall approach relative to the systems analysis effort is to conduct a continuing assessment and document yearly results so that they may affect programming of the following year's PPR program. During the FY89 analysis effort, the following activities will be conducted:

- o Coordinate with appropriate NASA Office of Exploration (OEXP) and Office of Space Sciences and Applications (OSSA) mission studies
- o Coordinate with other mission studies being conducted by offices at Johnson Spaceflight Center, JPL, etc
- o Convene a workshop of advanced mission planners and scientists in order to enumerate the mission alternatives
- o Conduct focussed trade studies to identify rover technology needs as a function of mission imposed requirements and constraints such as:
  - communication delays
  - traverse ranges (tens of meters to hundreds of kilometers)
  - operational times
  - navigation through lava fields

The overall approach relative to the integrated testbed is to first perform a one year definition phase in FY90. The end result of the definition phase would be a definition of functional requirements, functional design, risk assessment and a class A cost estimate for the implementation phase. The implementation phase would begin in FY91. Examples of key issues to be addressed and defined within the definition phase are as follows:

- o Mobility design
- o Navigation instruments and algorithms
- o Computer Architecture (probably space qualifiable prototypes)
- o Power source (probably not RTGs)
- o Communication links
- o Types and design of test courses
- o Design of remote command station (probably mobile)

ASSUMPTONS:

- o Funding estimates are in budget year dollars

MILESTONES/SCHEDULES:

- o Complete and document the first yearly system analysis study results (FY89)
- o Complete integrated testbed definition phase (FY90)
- o Complete integrated testbed implementation and demonstration in an outdoor test facility (FY92)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	244	2
FY90	600	4
FY91	4,300	4
FY92	3,300	3
FY93	4,000	2

A.3. LEWIS RESEARCH CENTER

A.3.1. POWER - SODIUM SULPHUR BATTERY

OBJECTIVES:

To demonstrate the potential for advanced sodium sulphur battery technology offering the following characteristics:

- o Energy density of 100 W-hrs/kg at the multicell battery level including the thermal management and single cell switching components
- o Service life of 1000 charge/discharge cycles at a 60% depth of discharge

DESCRIPTION

The sodium sulphur battery is a high temperature, high energy density battery in which the electrode materials are in the liquid state. The electrolyte is a unique solid ionic conductor material that is permeable only to sodium ions. Because of the high selectivity of the separator, the efficiency of the cell is very high. When operated at about 375 degrees C, the overall round trip efficiency of sodium sulphur cells is the highest of all contemporary devices. Like other nonaqueous cells, protective circuitry must be provided when these cells are grouped together to form a battery, This protective circuitry precludes damage to the battery in case there are one or more cells that become inoperative during the lifetime of the battery. Although sodium sulphur cells have been under development for about 30 years, there are still voids in the understanding and control of the decay and failure processes that are associated with the solid electrolyte material.

APPROACH

The U.S. Air Force has recently embarked on a major program to bring this technology to fruition for low earth and geosynchronous orbit applications. Much of these development effort is directly translatable to planetary rover power technology.

A better understanding of the electrolyte decay and failure modes are required for planetary rover applications. Recently developed acoustical microscopy is believed to be applicable towards providing new insights to this area. Ways to increases the useful life of individual sodium sulphur cells will be analyzed. An important portion of this effort will be the production of subscale experimental electrolyte formulations and subsequent stress testing. This will be followed by examination of techniques to evaluate the extent of decay of important structural features. Cycle life testing of cells is critical in the development of a reliability data base. Cell networking options as well as an overall battery design for the MRSR application will be performed as part of the effort. Cell selection criteria will be formulated based on the manufacturing characteristics of the cell populations as well as the battery networking options that are available consistent with over all cost, weight and reliability. Finally, a battery design (consistent with MRSR mission requirements) will be generated and the battery will be built and tested . The majority of this effort will be performed by industrial contractors

ASSUMPTIONS:

o Funding estimates are in budget year dollars

MILESTONES:

o Complete failure and decay models and test stand (FY90)
o Complete synthetic cycling tests (FY91)
o Complete electrolyte nondestructive testing (FY92)
o Compete Mars Rover battery final design, manufacture and testing(FY93)

BUDGET:

Year	Funding(K$)	Work-Years
FY89	0	0
FY90	600	3
FY91	700	3
FY92	500	2
FY93	700	3